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SYMPOSIUM ON THE AERIAL APPLICATION OF PESTICIDES IN FORESTRY

THE ASSOCIATE COMMITTEE ON AGRICULTURE AND FORESTRY AVIATION

OCTOBER 1987

Canada

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THE ASSOCIATE COMMITTEE ON AGRICULTURE AND FORESTRY AVIATION
NATIONAL RESEARCH COUNCIL CANADA

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Editor:* *George W. Green

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SYMPOSIUM ON THE AERIAL APPLICATION OF PESTICIDES IN FORESTRY

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Canadian Forestry Service

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FOREWORD

This Symposium on the Aerial Application of Pesticides in Forestry was organized by the Associate Committee on Agricultural and Forestry Aviation (ACAFA) of the National Research Council of Canada. It was sponsored by the National Research Council and the Canadian Forestry Service and evolved from needs that were expressed at a 1984 Symposium on the Future Role of Aviation in Agriculture which was organized by ACAFA and held in Saskatoon, Saskatchewan. Those needs are highlighted briefly in the opening remarks by the current Symposium Chairman which appear later in these Proceedings.

In retrospect, I think this Symposium achieved exactly what it set out to do. In its five technical sessions and through the 19 invited papers that comprised them, world experts in the fields concerned presented the state-of-the-art of that complex mosaic of disciplines which impinge on our ability to deliver aerially applied pesticides to our forests in the most effective, economical and environmentally innocuous way. Discussion periods following each of the technical sessions and a Wrap-up Panel Discussion at the end of the Symposium provided an opportunity for all 199 Symposium participants to contribute their knowledge and their experience to matters relating directly and indirectly to the Symposium theme. Records of these Discussion Periods are included herein extending the value of the Proceedings very significantly. A broad array of Poster Papers which complemented and expanded on the Symposium theme were displayed during the Symposium and 24 of these appear in published form herein adding immeasurably to the breadth and value of the Proceedings. These Proceedings, therefore, should provide a reference document of great value in the priorization and rational planning of further much needed research in aerial application technology be this for forestry or agricultural use.

Publication of the Proceedings has been delayed somewhat from the Organizing Committee's optimistic estimate. We had hoped that by providing detailed instructions to authors that we would receive camera-ready originals of all papers that could be printed virtually as received. While this was achieved for the most part, where content is concerned, variations in formation and in type face used by authors resulted in variations that would have detracted significantly, in the Editor's opinion at least, from the finished quality and aesthetics of the publication. It was decided, therefore, to have all papers typeset and I trust that the delay that this has caused is more than compensated for in the overall appearance of the Proceedings.

In editing the Proceedings, I have taken it upon myself to make such changes in formating that were required to provide consistency throughout. I have also taken it upon myself to make minor editorial changes, where required, to improve clarity without changing the sense of the presentation. These latter have been kept to the minimum and, in cases where I did not feel completely competent to insert a minor change, or where a major change was deemed appropriate, these were discussed with the authors concerned. I trust that the editorial freedom that I have taken has not changed the facts or the message that authors wished to convey. Should readers have any question about the printed word contained in the Proceedings, these should be discussed directly with the authors concerned.

Records of the Discussion Periods, including the Wrap-up Panel Discussion were transcribed from tapes made during the Symposium. These tapes were transcribed by the Session Chairman for each of the Sessions concerned who attempted to do this as literally as they could. Where any changes from the literal were required, they have attempted to capture the sense of what was said accurately. All of these transcriptions passed through me who, as Editor, took it upon myself to make minor editorial changes for the sake of clarity and/or brevity, referring back to the tape if this was deemed necessary. In some cases, it was impossible to pick up the name of a speaker from the tape or conversations being recorded were inaudible. These cases are noted throughout the records of these Discussion Periods in the Proceedings. All in all, I am satisfied that we have captured this aspect of the Symposium reasonably well and trust that we have not grossly misquoted anyone.

Appendices to the Proceedings include:

- Terms of Reference of the Associate Committee on Agricultural and Forestry Aviation
- Membership of the Associate Committee on Agriculture and Forestry Aviation (as per the Symposium date)
- The Symposium Organizing Committee
- Names and Addresses of Senior Authors of Invited Papers
- List of Registrants at the Symposium
- List of Exhibitors at the Symposium

The Organizing Committee hopes that this will provide a useful source of information for all readers of these Proceedings.

A copy of the Symposium Proceedings will be provided to all senior authors of papers included; to all exhibitors; and to all registrants at the Symposium. Additional copies, while they last, may be obtained at a cost of $25.00 per copy from:

Mr. Ken Charbonneau
Head, Conference Services
National Research Council of Canada
Montreal Road
Ottawa, Ontario
K1A 0R6

George W. Green
Editor
6 June, 1988

SESSION I

OPENING REMARKS AND THEME PRESENTATION

OPENING REMARKS BY ACAFA CHAIRMAN

The Symposium on the Aerial Application of Pesticides in Forestry is the second in a planned series of three symposia relating to the use of aircraft in Agriculture and in Forestry. The first, held in Saskatoon in April 1984, addressed the specific concerns of the agricultural community. Immediate benefits resulted, in terms of information dissemination, identification of research needs and coordination of federal government research capabilities. The third, planned for October 1989 in Winnipeg, is intended to assemble the user groups for the purpose of transfer of available research and development and to further coordinate the efforts of practitioners and scientists. The current and second Symposium, relating to the specific research requirements of Forestry under the sponsorship and leadership of the NRC and the CFS, has been undertaken to specifically examine the state-of-the-art as it applies to forestry and to identify immediate as well as mid-term research needs of the pest management aspects of forestry. If the results of this Symposium match those of the one on agriculture, and I am certain they will, then we will have taken a second large stride in the development of a concerted effort to improve pest management techniques.

Your Chairman for this Symposium, Dr. George Green of the Forest Pest Management Institute of the Canadian Forestry Service at Sault Ste. Marie, Ontario, has provided strong leadership in the planning, developing and implementing of this meeting and judging from the response, he can be justifiably proud of the content. He and his committee have worked long and hard to make this exercise a success.

Over the next three days an overwhelming array of topics and concepts will be presented, developed and discussed. But that is only a part of the responsibility of the Committee. The published Proceedings, expected to be in your hands sometime during the coming year, will provide the second guide post in the development of pest management practices. You will all be a part of this developmental process, because the concepts of the speakers, posters and exhibits will be augmented by the participating interaction of the audience. Dr. Green plans to assemble not only the speaker's papers and poster papers, but also the reactions of the whole assembly to complete the entire spectrum of technology and concepts.

I am proud to be associated with this developmental process, expect a first class symposium and look forward to seeing many of you in Winnipeg in 1989.

Charles H. Buckner
Chairman
Associate Committee on Agricultural
and Forestry Aviation

OPENING REMARKS BY SYMPOSIUM CHAIRMAN

G.W. Green

Forest Pest Management Institute, Canadian Forestry Service

It is a distinct pleasure for me as Chairman of the Organizing Committee for this Symposium to add my personal welcome to all of you to that just expressed by Dr. Buckner, Chairman of the National Research Council of Canada's Associate Committee on Agricultural and Forestry Aviation.

In September, 1984 the Associate Committee on Agricultural and Forestry Aviation, in association with the Saskatchewan Research Council, sponsored a Symposium on the future role of aviation in agriculture. That particular symposium was well received — so much so that, immediately following it, the Associate Committee decided to hold another one in 1987 — this time concentrating on the technology involved in the aerial application of pesticides in forestry.

It was felt then, and it still pertains today, that while we had made significant advances in our ability to apply pesticides to forests from the air since the early post World War II days when DDT (in rather massive dosages) replaced the calcium arsenate dusting of the 1920's and 30's against the spruce budworm and the hemlock looper, there was still a great deal that had to be learned of the fundamental physics and aerodynamics involved before further significant advances could be made in applying these materials from the air in a manner that would optimize targetability, effectiveness and efficiency and minimize off-target drift and environmental impact.

The time was ripe, we felt, to bring international experts in the field together to review the current state-of-the-art and to identify critical areas where research was lagging and where significant gains could be made by plugging these research gaps.

That is the task before us over the next few days. We have an impressive list of invited speakers to whom the Organizing Committee is most grateful. We have a cadre of knowledgeable and seasoned Session Chairmen who will keep things on line and on time. We have scheduled Discussion Periods following each of the technical sessions and a Wrap-up Panel Discussion Session on the final day which will provide an opportunity for everyone in attendance to contribute their knowledge and experience to the considerations at hand. We have a broad array of poster papers that complement and expand on the Symposium theme and we have a number of related exhibits that will further this cause.

I would say that we have all of the ingredients available for a tremendously interesting and productive three days, the ultimate success of which will depend, in a large part, upon the degree to which everyone of us in attendance gets involved. On behalf of the Organizing Committee, I invite you all to participate actively.

So without further ado, I would like to express my thanks, and I am sure yours to:

- The National Research Council of Canada and the Canadian Forestry Service for sponsoring this Symposium
- To the Organizing Committee and the Session Chairmen for their input to date — and that yet to come
- To the invited speakers without whom none of this would be possible
- To the authors of poster papers and to the exhibitors for their valuable contributions
- and last, but certainly not least to all registrants for their interest in this Symposium and the valued input that the Organizing Committee is confident they will contribute over the next three days to make this Symposium the resounding success that we are sure it will be.

To all of you, our sincere thanks and, if there is anything that the Organizing Committee can do to make your stay more productive and enjoyable, please feel free to contact any of us at any time.

OPENING REMARKS BY THE ASSOCIATE DEPUTY MINISTER, CANADIAN FORESTRY SERVICE

J.C. Mercier

Canadian Forestry Service, Ottawa

Mr. Chairman, Ladies & Gentlemen:

It is a pleasure for me to be with you today representing the Canadian Forestry Service and my Minister, The Honourable Gerald S. Merrithew, Minister of State for Forestry and Mines and to play a part, with the National Research Council of Canada, in the sponsoring of this timely and important Symposium on the Aerial Application of Pesticides in Forestry.

The Canadian Forestry Service has had a long and productive association with the National Research Council and with some of its associate committees. Our association with ACAFA (The Associate Committee on Agricultural and Forestry Aviation) is particularly strong as evidenced by the fact that the current ACAFA Chairman, Dr. C.H. Buckner, is a very recent retiree of the CFS, Dr. G.W. Green, still with the CFS, is acting as Chairman of this Symposium and Dr. J.A. Armstrong is co-chairman of the posters and exhibits sessions.

Canada is a forest nation. Forestry contributes more to our balance of international trade than agriculture, fisheries, fuels and mining combined and one in every 15 jobs in this country is dependant either directly or indirectly on forestry.

But Canada's forests are not limitless, as many would believe. We are approaching our annual allowable cut of softwoods in many parts of the country and exceeding it in some. We are running out of economically accessible wood supplies in some areas, and, we have realized that we must embark on extensive programs of intensive forest management if we are to maintain, enhance, and perpetuate wood supplies for this vital sector.

Forest protection is an integral and essential component of any comprehensive and viable approach to forest management. Where destructive forest insects and competing vegetation are concerned, it is of utmost importance that losses caused by these agents be maintained within limits incorporated in long-term forest management plans. Failure to do so will inevitably result in significant shortfalls in wood supply and in serious disruptions to regionally-specific harvesting plans.

As intensive forest management becomes the rule rather than the exception, as heavy investments are made in site preparation, in the use of genetically superior planting stock and in stand tending, and as the wood supply begins to come from a much reduced land base dedicated primarily to forest production, losses from destructive insects and competing vegetation become increasingly less tolerable.

Aerial application of pesticides (both chemical and biological) is one of the options available to forest managers, not only to reduce losses in forest productivity and maintain scheduled harvesting of these resources, but also to protect specific forest stands for aesthetic purposes, to maintain adequate habitat and food supplies for fish and wildlife and to allow forest cover to contribute optimally to the maintenance of sensitive hydrological balances. Often, under Canadian conditions, the use of aerially applied pesticides is the only effective and economically viable alternative available for these purposes.

Despite all of the scientifically sound arguments that those of us intimately involved with the forest sector in Canada can put forward regarding the use of pesticides in forestry; despite the rigour of federal registration requirements for forestry use pesticides under the Pest Control Products Act; and despite strong provincial rules and regulations with respect to pesticide use in forestry, use of these materials, especially from the air and on Crown forest lands in Canada, remains a major public and political concern of our current day society.

This public and political concern is often based on the belief, justified or not, that the materials used pose significant hazard to human health and place forest ecosystems at severe risk. It is also based on the belief that the aerial application of pesticides in forestry is less than precisely targetted and that large proportions of these aerially applied pesticides undergo significant off-target drift and deposition.

The Canadian Forestry Service shares similar concerns but from a somewhat different viewpoint. We are confident that the Canadian pesticide registration and regulatory system is sufficiently rigorous that registered pesticides, when used carefully and as directed, pose little risk to human health or to environmental quality. By the same token, however, we are dedicated to the principal, as is the forestry sector generally, that pesticides be used only when other forest protection options will not provide the level of forest protection required or are logistically or economically impractical. We are also concerned, from an ecological sense, that ways and means be developed to deliver aerially applied pesticides to the specific target as accurately as possible and in the minimal amounts required to achieve protection objectives.

This makes economic as well as ecological sense. Pesticides are expensive, application costs are high and, hence, it is economically prudent to reduce the amount of pesticide used in any treatment and to extend the area that can be treated per lift of the aircraft applying the pesticide as much as possible.

If it is possible to introduce technological improvements in these areas through R&D, the forest sector will benefit directly, the potential for negative impacts on the environment and on human health will be reduced even further, and we will be in a better position to allay, with hard fact, significant elements of concern that the public and political decision makers have for the use of aerially applied pesticides in forestry.

Within the Canadian Forestry Service, the National Research Council, various provincial forest authorities and some universities in Canada, we are investigating various aspects of pesticide aerial application technology. But this field is tremendously complex, research costs are high, and the collective expertise that we have to bring to bear is scarce, widely dispersed and under-resourced. I suspect that this situation is not unique to Canada. I also expect that fiscal restraint will be the order of the day for all of us for some time to come.

Given the scenario, it would seem very timely and very worthwhile to review critically the state-of-the-art in this complex field, to examine critical gaps in our knowledge of it, and, whenever practical and possible, to marshal our collective expertise in a cooperative approach to this problem.

The purpose and theme of this Symposium on the Aerial Application of Pesticides in Forestry would appear to be directly attuned, from the technical perspective at least, to these needs. The Symposium has attracted an impressive list of invited speakers, all internationally recognized experts in key technical aspects of the aerial application of pesticides. A wide range of poster papers (27, I believe) will add breadth and depth to the Symposium theme. A number of exhibitors will demonstrate related wares and technologies. And last, but certainly not least, Symposium attendees from many parts of the world will be given the opportunity to contribute their particular knowledge and experience to the Symposium in the discussion periods that follow each of the sessions and in the wrap-up session on the last day.

All of the ingredients would appear to be there for a most productive approach to an important real-life problem.

On behalf of the Canadian Forestry Service, I welcome all of you to Canada and to the nation's capital. I am pleased to be part of this Symposium. I look forward to the Proceedings that will emanate from it. And I wish you all success for stimulating and productive consideration of a most important topic over the next few days.

Thank you.

FOREST PEST CONTROL: A SOCIETAL AND A TECHNICAL CHALLENGE

J.R. Carrow

Faculty of Forestry, University of Toronto, Toronto, Ontario

In recent years, Canada's forestry sector has spent a lot of time talking about gaps. In our eastern boreal forest, the resource base for our pulpwood and softwood lumber industry, we have a "regeneration gap", the product of inadequate regeneration of harvested and burned areas over the last 40 years. This in turn is expected to produce a "wood supply gap" early in the next century, during which, for a period of 10 to 20 years, it may be very difficult to provide the industry with an economic supply of fibre. And of course, like so many other sectors, we too have our own "communications gap" — the public simply doesn't understand our problems. Of more relevance to this symposium, we also have a serious gap in "pesticide technology", and while pesticides are a thorn in our side as we try to improve communications with the public, we all recognize that they are absolutely essential if we are to successfully bridge the other two gaps in regeneration and wood supply.

The technology gap for forest pest control and management should concern us all. We are living in an era when the need for pesticides is intensifying and becoming more site- and pest-specific, yet it is a time when we are losing effective pesticides in Canada faster than we are developing new ones. In recent years, we have witnessed a major struggle to register and approve two new herbicides for aerial use in forestry — glyphosate (Vision=Roundup) and hexazinone (Velpar). At this time, only one registration (Vision) has been successful. Simultaneously we have lost 2,4,5-T and efforts to register a replacement herbicide, triclopyr (Garlon) have been thwarted by agencies who have successfully prevented field testing. Insecticide technology is only slightly better off. A 10-year Canadian effort to develop and register a new spruce budworm insecticide, permethrin, for aerial application has been unsuccessful, even though an aerial registration for agriculture is in place. Concurrently, most eastern jurisdictions have converted their spruce budworm spray programs entirely to the microbial insecticide, *Bacillus thuringiensis kurstaki* (B.t.k.), with the result that the demand for chemical insecticides has dropped sharply. One of these, aminocarb (Matacil), has served for over a decade as a highly cost-effective material and is generally regarded as having low environmental impact, but with declining demand in Canada, the manufacturer is expected to stop production of Matacil this year. Thus another valuable tool is lost.

The reasons for this gap is pesticide technology are varied and complex. A special Task Force, operating under the aegis of the Canadian Council of Resource and Environment Ministers (CCREM), spent three years trying to improve the process of pesticide development and registration, with only limited success. The Task Force discovered that pesticide development and registration for forestry use is seriously delayed, and often prevented, by a whole series of institutional obstacles — obstacles which relate to policies adopted by the pesticide manufacturers, the federal and provincial regulatory agencies and even some forest management agencies (Carrow 1985). Bridging the current gap in regeneration and the future gap in economic wood supply, which I referred to earlier, will require that we have the technology to control competing vegetation and insect pests. In an attempt to ensure that these gaps are successfully bridged, forest managers across Canada are setting site-specific, time-related production targets on old-growth stands and on newly-established stands — targets that require that those stands produce a specified amount of fibre in a specified time. One clear example of this is the practice of J.D. Irving Co. in New Brunswick, which now signs its new plantations with a planting date and a harvest date, for example, "black spruce planted in 1980 for harvest in 2020". Implicit in that sign is that the plantation must achieve an operable volume in 40 years — a process that depends heavily of the availability of pest control technology.

So the need for this technology is evident and indisputable. That technology will have to be cost-effective, practical and commercially available. But perhaps most important, it will have to be socially acceptable.

I'd like to focus now on this latter issue — social acceptability, which sooner or later, translates into public support. While the forestry sector in Canada has historically ignored the importance of public support for forest management, two factors make it imperative that we do so. First, 92% of the productive forest land base on which resource managers practise their craft is owned by the public of Canada. Second, that same public provides the great majority of funding required to carry out the practices necessary to ensure a continuous flow of benefits from the resource. Historically, we have neglected public support, but just how important this is, was made clear to all who attended the National Forest Congress held in this city just 18 months ago. That Congress brought together over 400 spokesmen and leaders from every group that has a stake in Canada's forest resource. The Congress focussed on the major issues: trade, wood supply, jobs, environment and multiple use, and at the conclusion, Canada's forestry ministers announced a 4 million dollar public awareness program designed to improve Canadians' understanding and awareness of the importance of our forests to our economy, our environment and our lifestyle (Canadian Forestry Association 1986). Several participants were discouraged by the type and level of this commitment, but the Ministers responded that they would be unable to argue successfully for increased forestry funding in Cabinet until their constituents, the public, developed a much better understanding of forestry in Canada, and the need to manage now in order to ensure future benefits. Until that understanding develops, the public will continue to lobby for social programs with immediate benefits — public day care, improved health care, new schools, support programs for minority groups.

Public support then is critically important — more now than ever before, because that public is placing increasing demands on the resource. Support, of course, is shaped by opinion and it is interesting and somewhat startling to examine what public opinion says about our forest resource. First that public is highly urbanized — about 80% of Canadians now live in urban centres, distanced both physically and economically from the forest land base. Several generations of Canadians have now grown up with an abstract association with the resource and a different sense of land ethics and resource stewardship. It should come as no surprise then that this urban public, which enjoys one of the higher standards of living in the world looks to the forest environment as a source of benefits *other* than direct income. Some opinion polls are telling. A recent national poll by Decima showed that, in terms of priority for government action, Canadians ranked "environmental quality" number one, ahead of major economic issues, such as unemployment and free trade. This high ranking for environmental quality is not a new phenomenon. Canadians have consistently ranked it important for about a quarter of a century now. It is a value that is not only persisting, but increasing in importance. Of interest also is a poll of 7,000 Canadians conducted recently (Lien 1987) in which people were asked to indicate what values they associated with the forest environment. Listen carefully!! The value most commonly mentioned was *spiritual*, next were aesthetic value, ecological value and recreational value in that order. The least mentioned value was utilitarian (or economic) value. The *ranking* of values in this survey is not as important as the *range* of values, because it illustrates that the public expects forest managers to provide a wide range of benefits. To a large extent, how well the non-industrial forest values are preserved and enhanced will determine the level of public support forth-coming for forest management.

You will note that I have been talking about values and the forest resource — economic and social values, but clearly human values. What we are witnessing is an evolution of human values, as they relate to our forest environment, and the consolidation of those values is emerging as a new resource ethic — one that places high value on the more abstract attributes such as aesthetic and spiritual benefits. I can assure you that trying to manage a renewable resource for industrial wood supply in the context of ever changing human values is a tough enough challenge, but try managing for spiritual benefits as well. We haven't been *teaching* our foresters how to manage for spiritual and aesthetic values, but we had better start if we want to retain primary responsibility for management of that public forest resource. For in any dispute, human values present a far more powerful case than arguments based solely on logic and reason. We have many examples in forestry, the most recent being the government decision to withdraw the South Moresby archipelago — an area the size of Prince Edward Island — from the productive forest land base of British Columbia and declare it a national park, despite the fact there were several reasonable proposals for integrated use which would have accommodated logging, wilderness, recreation, and wildlife habitat. However, the issue was polarized by the national media and portrayed simplistically as a choice between clearcut logging and preservation of a unique ecosystem (a "Canadian Galapagos") and native culture — a choice between economic gain and preservation of human values. It was no contest! Similarly, public pressure in Ontario, Quebec, Nova Scotia and Maine has brought about conversion of their spruce budworm spray programs from highly cost-effective chemical insecticides to the more expensive, but more acceptable microbial insecticide, *Bacillus thuringiensis kurstaki* (B.t.k.). In only three years, the proportion of chemical spraying in Canadian budworm programs declined from 97% to 26% (Morris *et al.* 1986). And at the same time, pressure from other publics have thwarted three years of field testing of the herbicide, triclopyr (Garlon), to gather environmental impact data in support of registration for forestry use. Just how complex the situation can become was evident in the outcome of the challenge to the forestry use of 2,4,5-T in Nova Scotia. After a lengthy trial, which must rank as the most exhaustive legal examination of a pesticide in history, the Nova Scotia Supreme Court (Nunn 1983) ruled that forestry use was not unduly hazardous to health, thus providing a powerful legal basis for regulatory bodies in Saskatchewan, British Columbia and Ontario to lift their provincial suspensions of 2,4,5-T. Yet they refused to do so, using the lame and inappropriate argument that there was no need to lift the suspension since the primary manufacturer, Dow Chemical, was stopping production. Meanwhile, the manufacturers and distributors were, in turn, using provincial suspensions in Canada as one argument to support their decision to phase out 2,4,5-T.

All of this taken collectively illustrates that we are in a period of intense public scrutiny of forestry practices in Canada. Much of this scrutiny surfaces initially as criticism. We should welcome public scrutiny and criticism for several reasons. First, and foremost, criticism denotes interest — and broad public interest in our forests is a rather new phenomenon in Canada. Second, it provides an opportunity for us to explain to the public what good forest management entails — to explain that it involves much more than planting trees, to explain the need for proper tending of those trees to prevent stagnation, to explain the need for protection of those trees and public investment from the devastating damage caused by insect epidemics. Interestingly, there is some evidence that the general public is not opposed to spraying of our forests. A recent survey in British Columbia (Anonymous 1987a) showed that 73% of those polled believe that chemical spraying of our forests is justified if the resource is at stake. Furthermore, a canvass of public opinion in Ontario last year showed that 80% of the respondents approved of the government's proposed insect spraying program, which involved a combination of chemicals and B.t.k. These two examples represent the views of the *general* public — a cross-section of occupations, age classes, and socio-economic levels — and they should influence policy. But as Ambassador Allan Gottlieb pointed out recently at the Canadian Forestry Forum, we are moving away from the era where public policy was shaped by broadly-based public interest groups, and are now in a period where narrowly-focussed special interest groups with a limited constituency are influencing public policy to a greater extent.

Your symposium will focus on the science and technology of aerial application of forestry pesticides. I have tried to describe the socio-political environment in which forestry practises, including pesticide application, are carried out. I have also emphasized the critical importance of public support for forestry. I can think of no aspect of forestry that presents a greater challenge for public support than does pest control and pesticide application. But it is a challenge that we can overcome if we adopt a responsible and progressive attitude about pesticide use. As with so many of man's pursuits, the answer lies not in the simplistic question "to spray or not to spray?" but rather in a balanced approach which utilizes the available and approved technology to address our immediate pest control needs, while at the same time substantially increasing our R & D effort to develop acceptable alternatives to chemical pesticides. Nor is the answer simply alternatives; for the near future, the answer is *every* technology we can develop and apply to satisfy the increasingly complex challenge of forest pest control. If we want to retain and build on public support, we must remember that we are primarily in the business of *protecting* the forest resource. We are *not* in the business of using chemical pesticides or biological pesticides, and it is indeed distressing to hear spokesmen in the forestry sector cling relentlessly to one form of pest control over another solely on the grounds of cost-effectiveness, without regard for public acceptability. We must accept that public opinion now plays and will continue to play a powerful role in forest management practises in Canada. We have two choices: we can resist public sentiment, in which case, we run the risk that much of the management responsibility will ultimately be removed from forest managers, or we can be responsive to public sentiment and use it to help gather support for the development of new acceptable technology. The world is changing rapidly, and so is the forest and the values associated with it. Forest managers must adapt to these changes and use public opinion positively to help develop new pest control technology. In his futuristic book "The Third Wave", Alvin Toffler (1980) points out that a major factor leading to the demise of the railroad industry in America was that the railroad companies thought they were in the business of running a railroad. What they failed to recognize was that they were in the business of transporting goods and people. Similarly, we must remember that we are in the business of renewable resource management — management of a renewable public resource to provide a continuous flow of benefits, and I might add, using technology that is publicly acceptable. To accomplish this, pest control technology is essential — to preserve standing timber inventory, to maintain annual growth, to preserve wildlife habitat, to maintain aesthetic values and to prevent stagnation of young trees. That technology is absolutely vital to the achievement of management goals, but the nature of that technology will change dramatically in the next decade. Microbial insecticides — B.t.k. and insect viruses — have already replaced chemical insecticides in many operational programs, and it is likely that they will play an increasingly prominent role in forest pest control in the near future. The technology of pheromones and insect growth regulators is advancing steadily and we should anticipate that they will be used on a large scale to disrupt insect mating, to trap out populations and to disrupt normal insect growth and development. As well, the tactic of inundative parasite releases to suppress forest insect populations is under development. One of the encouraging signs is the recent interest of chemical companies in research on alternative control technology. In the past year, representatives of four companies historically involved in pesticide manufacture and distribution have approached me to discuss the potential for research and development on alternatives to conventional chemical pesticides, and at this time, several of them are actively engaged in this type of research.

Aerial applicators then should concern themselves with the technical challenges presented by these newer materials, several of which are biologically active and therefore must be handled with more care than conventional chemical insecticides. As well, herbicides are playing an increasingly important role in forest management, and it is clear that there is much to be done to improve the cost-effectiveness of aerial herbicide application in the forest environment.

Many of you are aware that, as an outgrowth of the 1986 National Forest Congress, Canada's forestry sector has developed our first National Forest Sector Strategy. This document was tabled and discussed at the Canadian Forestry Forum earlier this year, and endorsed by the Canadian Council of Forest Ministers last month. There are over 30 recommendations dealing with trade and investment, the forest and its management, employment, research, development and innovation and public awareness (Anon. 1987b). One recommendation deals very specifically with pesticide use in forestry.

I want to repeat the wording here, because it captures many of the points I have been making and hopefully will provide a direction for the next five to ten years.

"It is recommended that all elements of the forest sector recognize that pesticides are among the legitimate means for effective forest management in specific areas, that their use continue to be regulated; and:

- ensure that all pest management operations are ecologically and economically justified;
- encourage development and use of effective alternative methods of pest control, including integrated pest management;
- accelerate research into the environmental effects of pesticides; and
- ensure that the process for registration of pesticides for forest use is not cost prohibitive and is open to public scrutiny."

While this recommendation is not perfect, it does say a lot. You can see that the wording reinforces the position that pesticides are necessary and legitimate tools to achieve forest management objectives, but simultaneously points to the need for economic and ecological justification. In other words, pesticides should be used only in situations where there is a demonstrated economic need and where environmental damage can be limited to acceptably low levels. The recommendation also urges the development and use of alternative control methods, as well as increased research on the environmental effects.

The notably balanced nature of this recommendation reflects two realities — the need for pest control, as well as the intensifying public concern about the use of chemicals in the forest environment. It constitutes *conditional* support for forestry use of pesticides. This will be a useful guideline for Canada's forest pest management specialists, both in operations and in research. These specialists have, in the past, displayed an impressive ability to adapt to regulatory pressure and to public opinion, and in so doing have established Canada as a world authority on aerial application of pesticides in forestry. When concerns about environmental damage or human health have arisen, they have generally faced those concerns directly and either answered them or adapted by changing application rates, pesticide formulations and carriers or dispersal systems. In so doing they have substantially improved our aerial spraying technology and have generally kept Canada's aerial spraying programs intact. These changes are also gradually building a base of public support for and confidence in aerial spraying. This support was not there 10 years ago. Considering the intensity of public criticism over the last ten years, that is an impressive accomplishment. With this record, I'm optimistic that our forest managers and scientists will respond positively to the message contained in our new National Forest Sector Strategy, and work vigorously to develop the new and more acceptable pest control technology that is so vital to the health of our forestry sector.

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SESSION II

PRINCIPLES OF SPRAY DROPLET FORMATION

PRINCIPLES OF SPRAY DROPLET FORMATION: THE ROLE OF EMISSION SYSTEMS

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ABSTRACT — Methods of characterizing the droplet size distributions of sprays, both theoretically and experimentally, are discussed in the context of forest spraying. Requirements for giving satisfactory needle deposits in a typical coniferous forest are discussed in relation to the use of various descriptors for droplet size distributions.

RÉSUMÉ — Les auteurs discutent [illegible] théoriques ou expérimentales, pour déterminer la distribution de la dimension des [illegible] en forêt. Ils traitent des caractéristiques permettant d'obtenir le dépôt d'une quantité [illegible] aiguilles des conifères d'une forêt typique et font une relation avec l'utilisation de [illegible] de [illegible] distribution de la taille des gouttelettes.

In the aerial spraying of forests, the size distribution of the formulation applied is critical to the success of the operation. Without a knowledge of this property of the spray a proper understanding of the mechanics of the process is impossible. It is essential to have at least a measure of the mean diameter of the droplets produced and the spread about this mean. Preferably the distribution of the mass over the full size range should be known. From this information, the distribution of numbers over the size range can be calculated and density of deposits, coverage of foliage and of drift losses, at least in principle, can be estimated.

In this presentation, the nature of droplet size distributions and their analytical description will be presented and related to practical needs in aerial spraying of forests. Measurements of the droplet size distributions produced by some widely used atomizing devices will also be reviewed and the practical use of the methods of characterizing droplet size will be briefly considered.

CHARACTERIZING THE SPRAY FROM AN ATOMIZER

Practical spraying devices produce a range of sizes of droplets. In what follows, the droplets are assumed to be spherical and not subject to evaporation. Definitions used will conform to those recommended by the American Society for Testing Materials (1981).

If the diameter of every droplet in a very large sample is known, the probability of finding a droplet in the size range D to D + dD can be defined as

$$P(D)dD$$

which is the statistician's probability density function based on number. It follows that

$$\int_{0}^{\infty} P(D)\,dD = 1.0$$

[illegible] is defined as the fractional number of droplets of diameters less than D,

$$N = \int_{0}^{D} P(D)dD \qquad 0 \leq N \leq 1$$

and

$$P(D) \equiv dN/dD$$

All information about the sample of droplets is contained in the function P(D). By suitable integrations, the distribution of mass over the droplet size range and various characteristic diameters can be obtained. The function P(D) is usually available in a discrete form, i.e. that the fractional number of droplets is known for each of a set of discrete diameter intervals, and approximations to the integrations are easily calculated.

Experimental data may be in the form of mass fractions in size classes, rather than as counts, but the transformations between mass and number distributions is computationally straightforward (Allen, 1975).

CHARACTERISTIC DIAMETERS

Characteristic diameters can be calculated from size distributions and one or more can be used to describe the sample. A simple example is the volume median diameter (half of the mass of the sample is smaller than this value). More generally, a characteristic diameter can be described as

$$D_{ef}$$

where e represents an entity such as volume, surface area, length or number and f is a fraction.

Nomenclature for the volume median diameter is therefore $D_v\ 0.5$. This value is one measure of the mean of the distribution and the width of the distribution can be expressed by the "relative span", which is defined as

$$(D_v\ 0.9 - D_v\ 0.1)/D_v\ 0.5$$

MEAN DIAMETERS

For specialized purposes, all the information required about the drops in the sample may be obtained from one of the many mean diameters which may be calculated. For instance, in calculating the efficiency with which pressure energy is converted to new surface area in atomization, the Sauter mean diameter is the only property of the size distribution which is needed (Mugele and Evans, 1951).

These specialized diameters can be calculated from the size distribution function or in some cases may be obtained directly from the measurement technique used. If the size distribution is known, the mean diameters can be calculated from its moments as follows

$$(\bar{D}pq)^{p-q} = Mp/Mq$$

where $M_k = \int_0^\infty D^k P(D) dD$

$\bar{D}pq$ = the mean diameter

and p and q can take values which reflect the entity being considered. For instance, the linear mean diameter, $\bar{D}_{10}$, is the same as the average value obtained if the diameters of all the droplets are summed and divided by the number of droplets.

The computational procedures used to obtain $\bar{D}pq$ will depend on the nature of the data available, but in principle if the size distribution is known in one form or another all possible values of $\bar{D}pq$ can be calculated. It is important to realize, however, that mean diameters are often sensitive to inaccuracies in experimental data that otherwise might be of little practical importance. If $\bar{D}_{10}$ is being calculated, the total number of particles in the sample is in the denominator and if the technique of measurement leads to uncertainties in the estimates of the number of very small droplets, negligible in mass terms, the calculated value of $\bar{D}_{10}$ may be seriously biased.

ANALYTICAL FORMS OF DISTRIBUTION FUNCTIONS

If the distribution of droplet diameters can be shown to be described accurately by an analytical expression, the treatment of experimental data becomes simpler. In atomization research, the properties of a spray can then be described by a small number of parameters and their correlation with independent variables such as pressure and fluid properties becomes more straightforward.

When the details of breakup of liquids into droplets are considered, it is clear that since several mechanisms may be operating in the same device, there is no reason to expect that the size distributions will all conform to the same analytical expression. Notwithstanding this fact, analytical forms can still be useful in the analysis of spraying experiments. The functions most commonly used will be discussed.

Analytical forms of P(D) must have the general properties of $P(0) = 0$ and $P(\infty) = 0$. The function in principle need not be continuous with a single peak (droplets formed from a spinning disc, for instance may be either primary or satellite droplets with none in between these two peaks). In most devices of commercial importance, however, a smooth curve with a single peak is observed.

Analytical forms commonly used have their origin in common statistical distributions. Their relationships to the nature of the breakup sequences have been described by Takashima, 1979. The Poisson distribution, for instance, underlies the Rosin-Rammler equation:

$$1 - f_v\ (D) = 1 - \exp\ (-(D/\bar{D}RR)^n)$$

where fv(D) is the volume fraction of liquid in droplets smaller than D, $\bar{D}RR$ is a characteristic mean diameter,

and n is a parameter indicating the size span of the distribution.

This distribution is widely used to describe the comminution of solids but though often cited is not favored in atomization work. It has the considerable disadvantages that there is no upper bound to D, and that if $n \leq 3$, the number of droplets approaches infinity as $D \rightarrow 0$.

The distribution of Nukiyama and Tanasawa (1938) is derived from the Gamma function. It can be expressed as

$$\frac{dN}{dD} = aD^m \exp(-b\ D^n)$$

where N is the number of droplets smaller than D,
a is a term obtained by integration over D,
and m, b and, n are adjustable parameters.

The term m is generally set at 2. If n is fixed, the distribution has only one adjustable parameter, which is advantageous in terms of data-reduction but unfortunately most size distributions are not accurately described by this special case.

This distribution has been used widely but because it allows a small but finite number of very large drops, mean diameters calculated from it may be inaccurate (Mugele and Evans, 1951).

Distributions derived from the Gaussian error curve form another class of useful functions. The simplest possible form may be written as

$$N = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{D} \exp\ (-½(\frac{D - \bar{D}_{10}}{\sigma})^2) dD$$

where
σ is a measure of dispersion,
and $\bar{D}10$ is the arithmetic mean diameter.

Measured distributions seldom conform to this form because they are usually skewed towards the small drop ranges, and several variants of this distribution have been proposed. The log-normal distribution is:

$$N = \frac{1}{\sqrt{\pi}} \int \exp\ (-z^2) dz$$

where $Z = K \ell n (D/\bar{D}gm)$

$\bar{D}gm$ = geometric mean diameter

$K = 1/(\sqrt{2}\ \sigma gm)$

and σgm = standard deviation of the geometric mean diameter.

This distribution is easily transformed to the mass-based form and the two parameters are simply extracted from experimental data by graphical means (Allen, 1975). It has been found desirable in practice however, to modify this equation to reflect the reality of an upper bound on D. This is done by the use of the upper-limit log-normal distribution (ULLN),

$$Fv(D) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{T} \exp(-t^2)dt$$

where $T = \delta\ \ell n (A\ D/(D_{max} - D))$

D_{max} is the upper bound droplet diameter

δ is a measure of dispersion

A is a measure of skewness.

This expression is more flexible in fitting to experimental data but at the cost of a third adjustable parameter, D_{max}. Goering and Smith, 1978, have described a systematic method for obtaining best estimates of the three parameters.

REQUIREMENTS FOR FOREST SPRAYING

Currently available atomizing devices mounted on aircraft can produce wide ranges of droplet sizes. In practice, control of the median size of the distribution produced is possible, and also, to a limited extent, the relative span of the distribution.

In forest spraying, operators and regulators have designed effective systems for spreading pesticides which use remarkably small quantities of active ingredients per unit area of forest treated. The basic requirements for such spraying can be worked out from simple mass balance arguments and related to droplet size distributions of emitted spray. The arguments presented here are based on New Brunswick operational methods, on some of the experimental results of the Dunphy trials, as well as results from our laboratory.

In New Brunswick in 1986, over 350,000 hectares were sprayed with up to 210 g Sumithion/ha by aircraft using hydraulic nozzles or rotary atomizers.

The forest which was sprayed in the Dunphy trials had, on average, 3.2 m^2 of foliage per m^2 of ground. Under favorable circumstances, about 50% of the emitted spray reported to the foliage in the first 400 m downwind. If the forest is considered to consist of balsam fir (needle area about 0.22 cm^2) it is possible to estimate the droplets deposited per needle under ideal circumstances. If the emitted spray is monodisperse, the number of droplets deposited per needle are shown in Table 1A. The rule-of-thumb that a deposit of about one drop per needle will give satisfactory results suggest that if monodisperse droplets could be generated, the chosen size should not exceed about 50 μm.

Actual sprays are not monodisperse but similar calculations can be done if suitable initial distributions are used and assumptions are made about the efficiency with which foliage collects droplets. This calculation has been done using a size distribution typical of spray from a TBM aircraft spraying emulsion from hydraulic nozzles. To simplify the calculations, the distribution has been represented by seven droplet diameter classes (Picot et al., 1986). The overall collection efficiency has been adjusted to 50%. The collection efficiency for each size class has been estimated from field data from the Dunphy trials and is representative of wind speeds in the canopy of about 1 m/s. The results of the calculation (Table 1B) shows clearly that the middle size range of droplets provide most of the coverage. Droplets larger than about 40 μm (54% of the mass) are irrelevant in terms of supplying satisfactory number of droplets per needle.

TABLE 1: Average Deposits in Droplets/Needle
210 g AI /hectare, 50% to foliage

A	Monodisperse Droplets Generated							
Dp μm	5	10	15	20	30	45	55	80
#/needle	1073	134	40.2	17	5.0	1.5	0.82	0.27

B	Using a Typical Polydisperse Distribution						
Dp μm	2.6	10.6	21.2	31.8	42.4	53	95.4
Δm	0.0015	0.1485	0.12	0.19	0.20	0.15	0.19
eff'y	0	0.065	0.41	0.54	0.55	0.63	0.70
#/needle	0	1.49	0.96	0.56	0.27	0.12	0.02
cumulative #/needle	0	1.49	2.45	3.01	3.28	3.40	3.42

Returning to the question of the application of descriptions of the size distribution to practical problems, several points become clear. First, there is a lower limiting size, here about 10 μm, below which droplets are collected with such low efficiency that they are ineffective in adding to foliage deposits. Second, above a certain upper limiting size, coverage is so poor that material is largely wasted. Third, that the relative amount of the sprayed material smaller than the lower limiting size is important but that its distribution need not be known in detail. Fourth, that relatively few of the largest droplets may represent a significant fraction of the mass of the spray and a knowledge of their size distribution is important in spray accountancy.

It is clear that if the principal concern about a specific spraying operation is in maximizing the deposit on foliage, the most effective means of specifying the distribution is by the mass fractions in the desirable range.

SOME EXPERIMENTAL RESULTS

In this section, some typical experimental measurements of size distributions of sprays of interest in aerial spraying of forests will be examined in the context of the priorities defined above.

These measurements were made by the Spray Technology Group at the University of New Brunswick and a brief account of the technique used is necessary. Details have been described elsewhere by van Vliet and Picot (1987).

These measurements were made by mounting the atomizers in a once-through wind tunnel 1.0 m in diameter and measuring the spray produced by traversing the plume with two probes (supplied by Particle Measuring System, Inc.). The first probe used was a forward-scattering laser spectrometer, (FSSP-100) which is designed to measure particles from (approximately) 0.5 μm to 50 μm in diameter. The second probe used is an imaging spectrometer (OAP-260X), which has a nominal range of 10 μm to 600 μm. The probes measured the flux of droplets in each size class through the sampling plane 1.0 m downstream of the sprayer. The temporal average size distributions for each probe were obtained by systematically traversing the sampling plane in two co-ordinates orthogonal to the flow direction and summing the resulting counts. The forward-scattering probe was calibrated and the total mass flux of droplets in the range sensed by it was calculated. The sampling area of the other probe is less well-defined and it was, in effect, determined by attributing the unaccounted for fluid to droplets of sizes greater than reported by the forward-scattering probe. In other words, the mass balance was used to specify the effective sampling area of the probe. Probe calibration methods are discussed by Hovenac (1986) and van Vliet and Picot (1988).

If the measuring instruments gave exact results, and there were no errors in experimental procedure, the size distributions when plotted would give a smooth transition from the size range of one instrument to the other. Unfortunately, this is not always observed. Instead, the imaging probe appears to underestimate the number of droplets in the lower size ranges and a typical cumulative volume plot shows a sag between 50 and 100 μm. The spectrum is also broadened to an unknown extent, the effect being greatest for the smallest drops in the OAP-260X range.

Near the upper limit of the size distribution, the nature of the distribution becomes of some practical importance if the fractional mass in the desirable range is to be determined. If the sample is large enough, the counts of the largest droplets become statistically significant enough that the distribution of mass becomes sufficiently accurate for practical purposes. If not, some form of distribution may have to be assumed. This and other problems have been discussed by Tate (1982) as well as others but there is not consensus on what analytical form of distribution gives the most representative results.

A FLAT FAN SPRAY

The Teejet 11010 flat fan spray nozzle has been used for many years to spray an emulsified formulation of insecticide. Aircraft speeds at least as high as 76 m/s are commonly used. Wind tunnel testing of this nozzle (spraying 3.8 L/min (1.0 USgpm) of a liquid of density 1 g/cm^3, viscosity 4 cP and surface tension 48 dynes/cm at 12.5°C at an air speed of 70 m/s will be examined.

Measurements were made by traversing the plume systematically at a downwind distance of 1.0 m, first with the scattering probe, then with the imaging probe. The number counts for each size class have been adjusted for sampling area and divided by the width of the size class in microns. The total number of droplets is equivalent to half the volumetric flow through the atomizer. This result is shown in Figure 1.

The results, when converted into cumulative volume and number fraction plots (Figure 2), show the consequences of underestimates of the counts in the lower range of the imaging probe. The experimenter is faced at this point with a dilemma. If the data are used in this form, no allowance will have been made for the droplets missed in the 50–100 μm range. All values of cumulative number fraction are therefore too large and any results derived from the data will reflect this bias. On the other hand, the experimenter cannot adjust the erroneous counts in a theoretically rigorous manner. The errors caused by the instrument cannot be quantitatively described, nor can the less-flawed data at the ends of the distribution be used to fair the join, since the analytical form of the distribution is unknown. When this problem is critical, high speed flash photography is used to enhance the data, giving independent information on the slope of the number distribution curve accurate for sizes above 70 μm. The overall result is generally of acceptable accuracy.

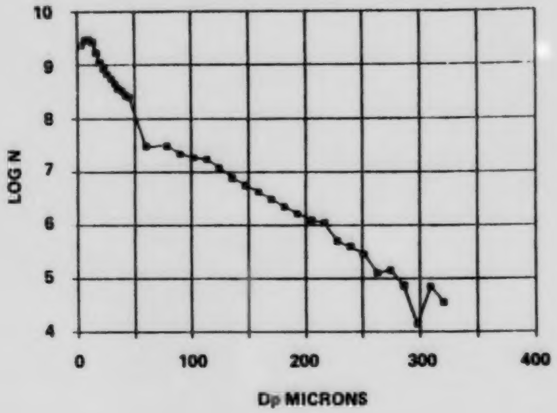

FIGURE 1: COUNTS PER SECOND PER MICRON VS DROPLET DIAMETER FOR TEEJET 11010 AT 3.8 L/MIN AND 70 M/S AIR SPEED

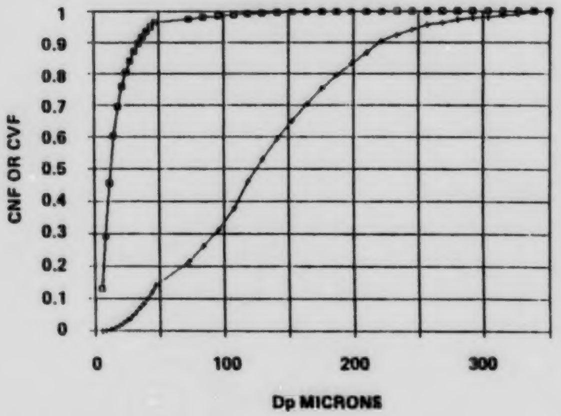

FIGURE 2: CUMULATIVE NUMBER AND VOLUME FRACTIONS FOR THE TEEJET 11010 AT 70 M/S AND 3.8 L/MIN.

This result, typical of size distributions of importance in forest spraying, also raises other points of interest. The hydraulic nozzle in aircraft service generates large numbers of very small droplets. In this example, the first three size classes (up to 11.74 μm) account for half of the number of the droplets counted (but only 0.4% of the volume). These droplets are of interest primarily because they are collected with low efficiency by foliage, and will be an important part of the spray which drifts off-target. Their presence is also important in the calculation of characteristic diameters. The $\bar{D}_{30}$ for this spray is 39.1 μm, a value which is numerically small because of the large number of small drops. Errors in evaluating the number of droplets in the smallest size classes, negligible in terms of volume frequency distributions, may have large effects in the calculation of some of the characteristic diameters.

A ROTARY ATOMIZER

Experimental results obtained from spraying the same liquid with an AU4000 Micronair atomizer are shown on Figures 3 and 4. The atomizer rotated at 14000 rpm, the liquid flow was 3.8 L/min (1.0 US gpm) and the air speed 48.2 m/s. The droplet size distribution was measured in the same way as described above.

In this case, nearly half the volume of the spray, and 99% of the number of droplets, were measured by the scattering probe. Again the join between the two distributions shows that the imaging probe is probably underestimating droplet numbers in its lower range and that some spectrum broadening is occurring.

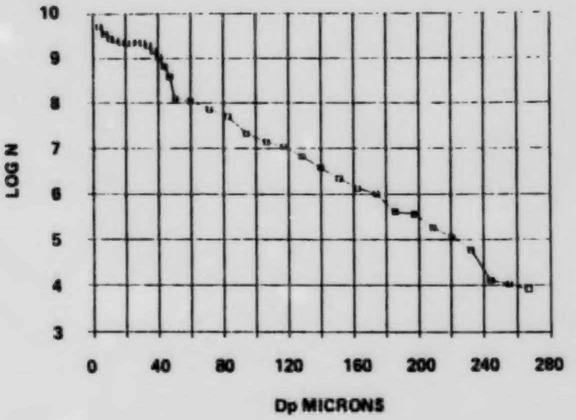

FIGURE 3: COUNTS PER SECOND VS DROPLET DIAMETER. MICRONAIR AU4000, 14000 RPM, 3.8 L/MIN, 48.2 M/S.

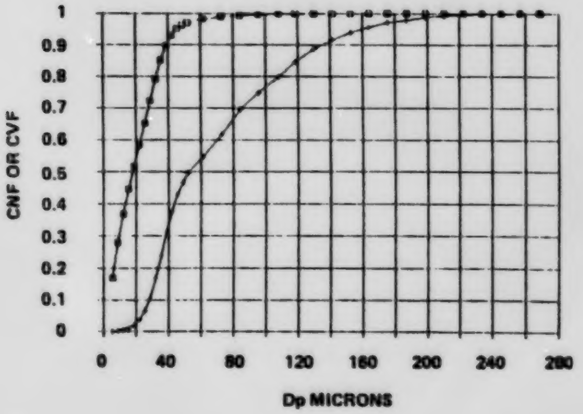

FIGURE 4: CUMULATIVE NUMBER AND VOLUME FRACTIONS CALCULATED FROM DATA OF FIGURE 3.

APPLICATION OF THE RESULTS

The purpose of such measurements is to evaluate the suitability of the spray generated for the task under consideration. In practice, it may be necessary to examine a range of variables such as aircraft speed, flowrate through the atomizer, changes in formulation properties, etc. so that the best alternative can be found. The definition of the "best" alternative depends on the requirements of the proposed spraying project. In other spraying applications, the definition of a crucial criterion may be dictated by more simple requirements. Chen and Lefebvre (1985), for instance, have argued that the characteristic diameter $\bar{D}_{32}$ is "the best indication of the atomization quality of a spray" when evaluating fuel injectors for internal combustion engines.

In our example, the spraying of coniferous forests for control of defoliation by budworms, the best size distribution has the highest proportion of droplets in a certain size range, which has (for various reasons not discussed fully here), been set at 15-55 μm. Other applications will, of course, require different criteria but in this case, this information is of crucial importance and the nature of the size distribution outside these limits is of interest mainly because it defines the mass of less efficacious material.

If the various descriptors of the sprays described earlier are calculated, the results are as shown on Table 2. It is clear from the definition of this problem that the characteristic diameters are less informative than the specification of volume fraction in the desired range.

Various analytical forms of distribution functions were applied to the data but the unknown errors in droplet counts in the 50-100 μm range limit the conclusions that can be reached. The upper-limit log normal distribution, which is the most flexible of those described here, could be fitted to the Micronair data to about 90% cumulative volume but failed to cope with the largest droplets.

The volume frequency distributions were calculated from the number data (Figure 5). The Micronair shows a sharp peak between 35 and 40 μm and a long tail at larger droplet sizes. This unusual shape cannot be expressed by an analytical expression based on the Gaussian distribution. The distribution resembles the sum of two separate overlapping distributions, one centred at 40 μm, the other at about 100 μm. This shape may reflect two distinct mechanisms of droplet formation by the atomizer.

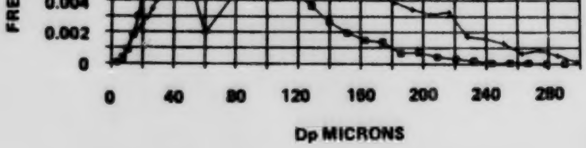

FIGURE 5: VOLUME FREQUENCY DISTRIBUTIONS FOR MICRONAIR DATA (SQUARES) AND TEEJET 11010 DATA (CROSSES).

The Teejet data, in the cumulative form (Figure 2), are obviously biased in the 50-100 μm range. If plotted as a volume frequency distribution (Figure 5), a discontinuity emerges in this range. Perhaps a technique could be devised to patch the two curves over the uncertain range on the basis of an analytical expression, but we have not yet attempted it. This case represents, however, an example of an experimental problem which might be solved by the use of analytical equations.

TABLE 2: Summary of the Characteristics of the Two Sprays

	Teejet 11010	Micronair AU4000
Dvo.5	125 μm	52.7 μm
Relative span	1.46	2.04
$\bar{D}_{10}$	17.9 μm	21.0 μm
$\bar{D}_{30}$	39.1	33
$\bar{D}_{32}$	84.9	50.1
Volume Fraction 15–55 μm	0.16	0.50

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PHYSICAL PROPERTIES OF LIQUIDS AND DROPLET FORMATION

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ABSTRACT — The physical properties of liquids playing a role in the formation of droplets are briefly presented. The mechanisms leading to the formation of droplets are then reviewed with an emphasis on the stability analysis of the liquid jet and of the liquid sheet. Experimental results supporting the theoretical analysis are summarized. The role of the physical properties of liquids is weighted against the effect of other variables affecting the drop diameter spectrum.

RÉSUMÉ — Les propriétés physiques des liquides ayant une importance lors de la formation de gouttelettes sont brièvement décrites et les mécanismes conduisant à la formation de gouttes sont présentés. Les principaux résultats de l'analyse de la stabilité des jets et des feuilles de liquide sont résumés ainsi que des résultats expérimentaux confirmant l'approche théorique. Le rôle des propriétés physiques des liquides sur la production de gouttelettes est mis en relief par rapport aux autres paramètres ayant un effet sur le spectre des diamètres.

NOMENCLATURE

a	arbitrary constant
B	wavenumber range, see equation 3d
d	droplet diameter
d_{32}	Sauter mean diameter
D	non-dimensional drop diameter $[d/l_o]$
D_{30}	non-dimensional volume mean diameter
D_a	drop diameter corresponding to the a% point on the cumulative drop diameter distribution curve
FN	flow number
k'	non-dimensional wavenumber
l_o	characteristic length
L	non-dimensional wavelength [wavelength/l_o]
L	non-dimensional co-ordinate in equations 2a and 2c
M	viscosity ratio $[\mu/\mu_g]$
M_n	nth moment of a distribution function
n	rheology index in the power law model
N	density ratio $[\rho/\rho_g]$
P	applied pressure
Q	flowrate
Re	Reynolds number $[\rho l_o V_o/\mu]$
t	time
T	non-dimensional time $[tV_o/l_o]$
V_i	ith component of the velocity vector
$V_{i,j}$	dV_i/dx_j
V_g	gas velocity
V_{gr}	non-dimensional initial velocity distribution in the liquid phase
$V_{g,gr}$	non-dimensional initial velocity distribution in the gas phase
V_o	characteristic velocity
We	Weber number $[\rho_g l_o V_o^2/\sigma]$
x,y,z	Cartesian co-ordinates
Z	Ohnesorge number $[\mu/\sqrt{(\rho l_o \sigma)}]$
α	viscoelastic relaxation time of a Maxwell fluid
β	non-dimensional growth rate [growth rate*l_o/V_o]
ϕ	viscoelastic parameter $[\alpha\sigma/\mu l_o]$
ρ	liquid density
ρ_g	gas density
σ	surface tension
τ	shear stress
μ	liquid viscosity
μ^o	zero-shear viscosity
μ_{app}	apparent viscosity
μ_g	gas viscosity

INTRODUCTION

In aerial spraying the control of the drop diameter spectrum of sprays emitted from a variety of nozzles is becoming a necessity in order to obtain better efficiency and to help reduce drift. It is well known that under similar conditions, spray formulations having different physical properties will produce different drop diameter spectra. This paper reviews the role of the physical properties of liquid in the formation of droplets. It is hoped that this discussion will help to establish the utility and the limitations of modifying the physical properties of spray formulations as a mean of controlling drop size.

1) PHYSICAL PROPERTIES OF LIQUIDS

There are essentially three physical properties involved in the mechanics of droplet formation. These are the density, the viscosity or apparent viscosity for fluids showing a non-Newtonian behaviour and the surface tension. The vapor pressure is not included in the list because it has no effect on the drop formation process.

1.1) Density

The density of a liquid is defined as its mass per unit volume. As most nozzle data are available for water a convenient way to present density data is the specific gravity which is the ratio of the fluid density to the density of water. Liquids are practically incompressible. Their compressibility coefficient is of the order of 10^{-5} atm^{-1}. Furthermore, temperature has little effect on the density of liquids. For example, water density at 20°C has a sensitivity to temperature changes of −0.02%/°C. Therefore the density of a given liquid can be considered as a constant over the range of pressure and temperature generally encountered in pesticide spraying. The specific gravity of liquids varies over quite a narrow range: ~ 0.80 to 1.20, with a few exceptions such as mercury with a specific gravity of 13.6.

1.2) Viscosity

Strictly speaking the viscosity is a property of fluids showing a Newtonian behaviour, in short Newtonian fluids. This property enters the equation of motion of fluid mechanics as a proportionality factor between the shear stress and the shear rate. In the simple case of a two-dimensional flow in the x direction we have:

$$\tau_{yx} = \mu \frac{dV_x}{dy} = \mu V_{x,y} \qquad (1a)$$

For a Newtonian fluid a plot of the shear stress as a function of the shear rate (called a rheogram) shows a straight line going through the origin (Figure 1). The slope of this line is the viscosity. Homogeneous nonpolymeric liquids have been shown to be Newtonian (Bird (1960)).

Some non-Newtonian fluid behaviours are shown on Figure 1. For these fluids the concept of an apparent viscosity is more appropriate. The apparent viscosity is defined as:

$$\mu_{app} = \frac{\tau_{yx}}{V_{x,y}} \qquad (1b)$$

Non-Newtonian fluid behaviour will be briefly reviewed. More details and numerous references on the subject can be found in Cheremisinoff (1983) and Perry (1984). The different fluid behaviours are referred to by various names. For clarity we will use the more descriptive names. There are essentially four types of non-Newtonian behaviour that are of interest for fluid in motion: shear-thinning, shear-thickening, time-dependency and viscoelasticity.

a) Shear-thinning

As can be seen on Figure 1, the shear-thinning behaviour is characterized by a decrease in the apparent viscosity as the shear rate increases. The proposed mechanism for shear-thinning is the gradual breakdown of the internal structure of the fluid as the shear rate increases. Mayonnaise, suspensions such as paint, some dilute suspensions of inert particles and polymeric solutions are examples of shear-thinning materials. The shear-thinning is the most common non-Newtonian behaviour.

b) Shear-thickening

Shear-thickening fluids experience an increase in their apparent viscosity as the shear rate increases. This flow behaviour is observed for concentrated suspensions of irregularly shaped particles in liquid.

c) Time-dependency

Time-dependency is characterized by a lag time between the change in shear rate and the associated change in apparent viscosity of a non-Newtonian fluid. This is shown in Figure 2. At time t_1 the shear rate is suddenly increased. From then on the apparent viscosity starts to adjust to this new flow condition and reaches an equilibrium value after some time. Time independent materials are really time dependent fluids requiring a very short time to react to a change in shear rate. As long as the rate of change in apparent viscosity to a step input is much greater than the rate of change in shear rate, time-dependency is irrelevant.

d) Viscoelasticity

Viscoelastic materials are liquids that behave like viscous fluids while showing to some extent the elastic property of solids. Purely viscous liquids stop deformation when the shear stress is removed but show no tendency to return to their initial undeformed state. In other words the deformation energy is never stored in purely viscous flows but is dissipated by "internal friction" while deformation occurs. On the other hand, viscoelastic liquids can store a part of the energy involved in deformation and restore it once the shear stress is removed. The energy is stored as normal stresses. This is why marked swelling in a jet of viscoelastic fluid issuing from an orifice can be observed (see Figure 3). The elastic behaviour is significant mostly during transitions like flow through orifices, restrictions etc.

A fluid may exhibit one of the types of behaviour described above over a limited range of shear stress and another one outside this range. For example (Figure 4) a fluid might be Newtonian (constant viscosity) under low and high shear rates and exhibit a shear-thinning behaviour in the intermediate range of shear rate. Such a behaviour is not uncommon.

Equations have been proposed to model the various non-Newtonian behaviours. Examples of these model equations can be found in Cheremisinoff (1983) and Bird (1960). These models have very little or no theoretical background and are basically empirical formulae.

The viscosity of liquids is temperature dependent. As temperature increases the viscosity decreases. Low and moderate pressures do not affect the viscosity of liquids significantly. Empirical and quite accurate formulae to estimate the effect of temperature on viscosity can be found in Perry (1984). Viscosities vary significantly from liquid to liquid. Viscosities ranging from 0.5 cP up to several thousands cP are possible.

1.3) Surface tension

A molecule inside the body of a liquid at rest is attracted towards the neighbouring molecules by the Van der Waals forces. Since each molecule has on average the same number of neighbours in all directions no net force can result (see Figure 5a). Now consider a molecule sitting in the layer just below a free surface. It is easy to see that this molecule will experience a net force perpendicular to the surface pulling the molecule towards the interior of the liquid body. Surface tension results from this phenomenon. Surface tension is the force that makes liquid jets cylindrical and droplets spherical. Surface tension makes the free surface of a liquid body behave like a thin solid membrane that can support a pressure difference.

The surface tension is affected by the presence of impurities in the liquid. Surface active agents are often used to lower the surface tension of a liquid. When a surface active agent is used, a newly formed surface will have a higher surface tension than an older one since a finite time is required for the surface active molecules to migrate to the surface. This phenomenon gave rise to the concept of a dynamic surface tension which is the value of the surface tension before an equilibrium surface is formed. This concept is illustrated in Figure 5b. The dynamic surface tension is a function of the age of the surface. Tabulated data on surface tension generally refer to the equilibrium surface tension. Haq et al (1979) present some surface tension data as a function of surface age for a few spray mixtures.

Numerically the surface tension of various fluids covers a range from about 10 dynes/cm to 75 dynes/cm. A remarkable exception is mercury with a surface tension of 485 dynes/cm. However the ratio of surface tension to the density which is a significant number for fluid flow typically ranges from 15 to 75 cm^3/s^2. Surface active agents can lower the surface tension of a liquid by a factor of 2 to 3 typically.

2) BASIC RESULTS FROM DIMENSIONAL ANALYSIS

Popov (1961) presents the dimensional analysis of the Navier-Stokes equation together with the boundary conditions appropriate to the atomization of liquid in a gas. He assumes constant physical properties which limits the analysis to a Newtonian incompressible fluid and gas as well as to isothermal systems. Otherwise the analysis of Popov is quite general and should apply to all atomizers. The main result of Popov analysis is:

$$D = f(Re, Z, M, N, V_{gr}, V_{g,gr}, L, T) \qquad (2a)$$

Equation 2a simply states that a non-dimensional droplet diameter can be expressed as a function of the parameters listed in the parenthesis on the right-hand side of the equation. The physical properties of the fluid and the gas are grouped in four parameters: Re, Z, M and N. Popov demonstrated with experimental data that the viscosity ratio M is of little significance and can be dropped. Furthermore we have seen in Section 1.1 that the density does not vary much from liquid to liquid. Accordingly we can also drop the density ratio N for atomization under typical atmospheric conditions. The Ohnesorge number Z can be expressed in terms of the Reynolds number Re, the Weber number We, and the density ratio N:

$$Z = \frac{\sqrt{NWe}}{Re} \qquad (2b)$$

Equation 2a may now be rewritten as:

$$D = f(Re, We, V_{gr}, V_{g,gr}, L, T) \qquad (2c)$$

It follows that under the restrictions outlined in the previous paragraph, the role of the physical properties of fluids in any drop formation process can be described by the two quantities Re and We. Popov (1961) presents data to support his analysis.

The Reynolds number describes the importance of the inertial force relative to the viscous force. It is inversely proportional to the viscosity. A Reynolds number smaller than unity implies that the viscous forces are larger than the inertial forces. Similarly, the Weber number is the ratio of the inertial force to the surface tension force. A Weber number smaller than unity means that the surface tension forces are larger than the inertial forces. The Weber number is inversely proportional to the surface tension. The choice of the characteristic length l_0, and of the characteristic velocity V_0 in the calculation of the Reynolds and the Weber numbers depends on the flow system under analysis. Throughout this paper we will indicate the exact meaning of l_0 and V_0 at the appropriate point in the discussion.

For non-Newtonian fluids the Reynolds number is written differently and other parameters need to be introduced. We will present two examples. The simplest model equation for non-Newtonian fluids is the power law:

$$\tau_{yx} = \mu^\circ \left| V_{x,y} \right|^{n-1} V_{x,y} \qquad (2d)$$

This model can reproduce shear-thinning and shear-thickening behaviours. The appropriate Reynolds number for this model is:

$$Re = \frac{l_0^n V_0^{(2-n)} \rho}{\mu^\circ} \qquad (2e)$$

The rheology index n should also be added to the list of non-dimensional parameters in the case of a power law model.

As a second example we consider the case of a Maxwell fluid, the simplest case of a viscoelastic behaviour. The model equation for a Maxwell fluid is:

$$\tau_{iy} + \alpha \frac{d\tau_{iy}}{dt} = \mu V_{i,y} \qquad (2f)$$

The corresponding Reynolds number has the usual definition but a viscoelastic parameter has to be added to the list of non-dimensional parameters to take the relaxation time α into account. The viscoelastic parameter can be defined as:

$$\phi = \frac{\alpha \sigma}{\mu l_0} \qquad (2g)$$

The dimensional analysis does not give the form of the function in Equation 2c. Such a function will depend on the spray system under analysis. To go one step further in the analysis we have to turn to the stability analysis of some basic flow systems.

3) INSTABILITY OF LIQUID JETS

No matter what technique is used to generate a spray, droplets always result from an instability of the free surface of the spray liquid (Drummond (1973)). In the absence of instabilities the liquid flowing out of a nozzle would remain as a continuous body of fluid and no droplets would result.

The purpose of the stability analysis is to identify the conditions leading to unstable motions and to predict the main characteristics of the instability. These are the mode, the frequency range for unstable motion and the growth rate versus frequency relationship.

The stability of a liquid jet has been studied extensively both theoretically and experimentally. We will first consider the motion of a laminar viscous jet in a vacuum. This problem has been studied by various investigators and Sterling (1969) reviewed the classical solutions of Rayleigh and Weber. The most unstable mode for a laminar jet is symmetrical. Figure 6 illustrates the symmetrical mode. It is easily seen that this is a truly unstable mode leading to the break up of the jet into droplets one wavelength apart.

The main results of the stability analysis are shown on Figures 7 and 8. The figures show the relationship between the non-dimensional growth rate and the non-dimensional wavenumber for various values of the Reynolds and the Weber numbers. Here V_0 is the jet velocity and l_0 is the initial jet diameter. These curves show a maximum at the wavenumber corresponding to a wavelength given by Sterling (1969) as:

$$L_{opt} = 2\sqrt{2}\,\pi \left[1 + 3\sqrt{\frac{NWe}{2Re^2}}\right]^{1/2} \tag{3a}$$

and the corresponding growth rate is given by:

$$\beta_{opt} = \frac{1}{\sqrt{8NWe} + 6NWe/Re} \tag{3b}$$

From Equation 3a it is readily seen that the most unstable wavelength increases with the Weber number and decreases with an increase in the Reynolds number. Therefore a high surface tension and a low viscosity reduce the optimum wavelength. Furthermore Equation 3b shows that a large Weber number and a low Reynolds number reduces the growth rate. These features are shown on Figures 7 and 8. From Figure 6 it is seen that a section of the jet one wavelength long results in one droplet (we neglect the satellite drop for now). Accordingly a relationship between the optimum wavelength and the corresponding droplet diameter can be written by taking the droplet volume as being equal to the volume of a section of the undisturbed jet one wavelength long. The result is:

$$D_{opt} = 1.88 \left[1 + 3\sqrt{\frac{NWe}{2Re^2}}\right]^{1/6} \tag{3c}$$

a relationship that satisfies Equation 2c. The 1/6 exponent in Equation 3c suggests that the physical properties affect the drop diameter by a small amount. For example with $Re = 10000$ and $NWe = 100$ we have $D_{opt} = 1.881$ and with $Re = 100$ and $NWe = 100$ we obtain $D_{opt} = 1.941$, a difference of $\sim 3\%$ only. However large variations in viscosity are possible leading to significant changes in droplet diameter.

If we assume that the jet instability is driven by a white noise signal we expect that the most unstable wavelength will dominate the break up process. Now, if we assume that the growth rate versus frequency curve is flat (no maximum), we expect that under a white noise excitation all the frequencies can lead to a break up of the jet and that the resulting drop diameter spectrum will be wide. On the other hand, if the growth rate versus frequency curve shows a significant peak around L_{opt}, one would expect a narrow droplet diameter spectrum. Therefore the droplet size dispersion is related to the flatness of the growth rate versus frequency curve. The wavenumber range defined by the intersection of the growth rate-frequency curve with a straight horizontal line at $\beta = a\beta_{opt}$ where $a < 1$, is a measure of the flatness and is related to the drop size dispersion (see Figure 8). It is shown in the Appendix that the wavenumber range is given by:

$$B = \sqrt{1 - a} \tag{3d}$$

Equation 3d is independent of the physical properties of the liquid. This surprising result is supported by data presented by Johnstone (1969) which are reproduced here in Table 1.

TABLE 1: Range Coefficient for Solid Stream Nozzles with Three Different types of Formulation (Johnstone (1969))

Formulation	Range Coefficient $(D_{75} - D_{25})/D_{50}$
Aqueous	0.52
Emulsion	0.52
0.4% hydroxyethyl cellulose	0.52

So far we have limited our discussion to the case where aerodynamic effects are insignificant. Aerodynamic effects become important when the Weber number is larger than ~1. When this is the case the main characteristics of the instability process are modified (see Figures 9 and 10). The wavenumber range over which unstable motion is possible is extended towards the region of smaller wavelengths. Also the wavelength corresponding to the maximum growth rate is shorter when aerodynamic effects are important. The growth rate is also larger for all wavelengths. The more significant effect is on the drop size dispersion. For $We < 1$ we have seen that the dispersion is not a function of the physical properties. When $We > 1$ the dispersion increases rapidly with the Weber number. The plotted values were computed using the modified stability theory of Sterling (1969).

As the jet velocity is increased (still higher Weber number) the mode of jet break up changes from the symmetrical mode to the atomization mode. In the atomization mode, droplets are formed in the immediate vicinity of the nozzle exit and the jet diameter increases with distance from the exit. Wu et al (1986) have shown that the linear stability theory of atomization predicts the right trend. The linear theory predicts that the volume mean drop diameter is given by:

$$D_{30} = \frac{b}{We}\, x_{max} \left[\frac{Re^2}{N\,We^2}\right] \tag{3f}$$

where the function x_{max} tends to 1.5 when its argument is larger than 1 and b is a constant of order 1. From Equation 3f it is seen that the mean drop diameter is inversely proportional to the Weber number. Therefore as the surface tension is increased the mean drop diameter should increase. Wu et al (1986) have also shown that the distribution of the drop diameter divided by the mean drop diameter is well described by a chi-square distribution with 28 degrees of freedom as shown on Figure 11. Therefore the only quantity required to describe the whole spectrum of droplet size is the mean drop diameter.

An other case of interest is the break up of a liquid jet in a crossflow. This problem has been treated theoretically by Adelberg (1968) and experimentally by Ingebo (1981). The experimental results of Ingebo agree reasonably well with the theoretical predictions of Adelberg. The following correlations were established by Ingebo (1981):

$$\begin{aligned} D_m &= 4.76/(WeRe)^{0.25} \qquad \text{for } ReWe < 10^6 \\ D_m &= 37.04/(WeRe)^{0.4} \qquad \text{for } ReWe > 10^6 \end{aligned} \tag{3g}$$

In Equation 3g V_0 is taken as the crossflow velocity and l_0 as the orifice diameter. These correlations are shown on Figure 12. Both high surface tension and high viscosity promote the formation of larger droplets. Adelberg (1968) also provides a relationship for the smallest drop size which reads:

$$D_{min} = a\left[\sqrt{\frac{N}{We}}\ \frac{1}{Re}\right]^{2/3} \qquad (3h)$$

As for the case of the mean drop diameter increasing surface tension and viscosity increases the minimum drop size.

The stability of non-Newtonian liquid jets is not fully understood. However the following observations can be made. According to the linear theory of the stability of laminar non-Newtonian jets, the growth rate is always larger with a non-Newtonian fluid than with a Newtonian liquid. Experiments by Goldin et al (1969) have confirmed this result. However the jets of a viscoelastic fluid do not break up as easily as shown on Figure 13. Initially the wave growth on a viscoelastic jet is comparable to the one on a Newtonian jet but at some point the wave growth stops and strings of droplets connected by thinning ligaments result. Bousfield et al (1984) have modelled this phenomenon by a numerical integration of the momentum equation. Their results are shown on Figure 14. The calculations reproduce the viscoelastic jet behaviour quite well. Figure 14 shows that the non-linear effects distort the sinous waveform initially imposed on the jet resulting in droplets connected by thin ligaments. Experiments have shown that this configuration can persist for a long time. Bousfield et al (1984) have shown that this stabilization effect in viscoelastic fluids can be attributed to the rapid buildup of extensional stresses in the valley of the wave.

Bousfield et al (1984) also present some interesting calculations which explain the formation of satellite droplets when a liquid jet breaks up. Satellite formation is shown on Figure 13. The satellite droplets are the small diameter drops formed in between the larger primary drops. Figure 15 shows the growth of a sine wave on two jets of a Newtonian fluid. In one case the viscosity is much higher than the other. For the highly viscous jet the wave growth is as predicted from the linear theory except for the distortion of the waveform. This distortion is an inertia effect that causes the most rapid growth to occur close to the droplet. As viscosity is decreased this effect is enhanced leading to the break up of a large droplet from a thin residual ligament which then collapses under the action of surface tension to form a satellite droplet. Shear-thinning fluids which are generally high viscosity liquids are known for their ability to reduce the number of small droplets. It may well be that the role of viscosity in satellite formation described in this paragraph can explain this characteristic of the break up of shear-thinning fluids.

4) INSTABILITY OF LIQUID SHEETS

The stability of a liquid sheet is a more difficult problem both theoretically and experimentally. In their inviscid analysis Hagerty and Shea (1955) showed that the sinous motion is the most unstable mode for liquid sheets. In the sinous mode the sheet thickness is constant and both faces of the sheet move in the same direction to create an S-shape pattern. Dombrowski and Johns (1963) included the liquid phase viscosity in their analysis. They reproduced the results of the inviscid theory and showed that the effect of the liquid viscosity is to reduce the growth rate and the range of unstable wavelengths. Their growth rate versus frequency curve shows a maximum. This is in contradiction with the theoretical results of Crapper et al (1975) who showed that for situations of practical interest there is in effect no maximum in the growth rate versus frequency curve. This is shown on Figure 16. Only for very low velocity sheets (NWe = 0.36) can a maximum exist and even then the curve is very flat. Note that the Weber number is calculated with V_o being the sheet velocity and l_o the sheet thickness. For sheet velocities of practical interest (NWe > 10) there is no real maximum in the curve. This result was later confirmed by an experimental study from Crapper and Dombrowski (1984). Some of their results are reproduced in Figure 17. It is immediately obvious that the growth rate is independent of the frequency. They concluded that the wave frequency observed on liquid sheets is dictated by the natural frequencies in the nozzle apparatus. The other interesting result from the analysis from Crapper et al (1975) is that the liquid viscosity does not affect the initial growth rate. This theoretical result is supported by experimental data.

To the author's knowledge there is no theoretical treatment of the break up of a liquid sheet in a crossflow. However some experimental data are available. Tomney et al (1978) present wind tunnel data for some aerial spray atomizers. Figure 18 shows some of their results for a Teejet nozzle. These nozzles produce a triangular liquid sheet when operated in still air. On the graph we have added predicted mean drop diameter shown as solid triangles. The prediction was made by correcting water data for the difference in surface tension between the two liquids. The emulsion has a surface tension of 19.9 dynes/cm compared to a value of 72.8 for water. The correction formula is:

$$d_{emulsion} = \left[\frac{\sigma_{emulsion}}{\sigma_{water}}\right]^{1/4} d_{water} \qquad (4a)$$

The corrected values are within 10% of the measured values. Note that this correction also applies for the liquid jet case as can be deduced from the first equation in Equation 3g.

The drop size distribution data from Tomney et al (1978) are shown on Figure 19. The graph shows that the data are well represented by the Nukiyama-Tanasawa distribution function. The Nukiyama-Tanasawa function is also suitable to represent drop size distributions from the break up of liquid jets in a crossflow. One feature of this distribution function is that all its moments can be expressed as a function of the magnitude b of the slope of the solid line on Figure 19. The n^{th} moment can be written as:

$$M_n = \frac{(n+2)\,!}{2b^n} \qquad (4b)$$

Therefore one can predict all the moments of the drop size distribution from the knowledge of the mean drop diameter.

Ingebo (1977) presents experimental data for a Simplex pressure nozzle. The Simplex nozzle is a single orifice nozzle with a tangential entry port producing a conical sheet of liquid. The data are reproduced in Figure 20. The regression analysis provides the following relationship:

$$d_{32} \sim FN^{0.4}\, V_g^{-0.75} \qquad (4c)$$

where FN is the flow number defined as:

$$FN = \frac{Q}{\sqrt{P}} \qquad (4d)$$

The flow number is linearly related to the discharge coefficient. The exponent of the gas velocity in Equation 4c is the same as the one which applies to the liquid jet problem (first equation in Equation 3g).

Although the coincidence in the numerical value of the exponent noted in the above paragraphs might be meaningless, it tends to suggest that the basic drop formation process is the same in the case of a liquid jet in a crossflow and in the case of a liquid sheet in a crossflow. This is not inconsistent with the theory of Adelberg (1968) which identifies the growth of wind generated surface waves as the primary break up process. Such a phenomenon can occur on a jet surface as well as on the surface of a liquid sheet.

5) CONCLUSION

The first point we would like to address in this conclusion is very basic. Throughout this paper we have tried to express all the results in terms of a few non-dimensional numbers, namely the Reynolds number and the Weber number. It should be emphasized that this is the most useful way to present data in the field of atomization of liquids. In fact this is the only technique one can use to compare quantitative results from various sources. There are still many papers that do not use the non-dimensional parameters or do not provide the necessary data to compute them. Remember that there are thousands of spray formulation-nozzle combinations but only a few non-dimensional parameters to characterize these combinations. From a quantitative point of view we would learn more efficiently about spray systems for aerial spraying if all the experimental data were to be presented in terms of non-dimensional parameters.

Two of the results that have been presented appear to be of significant importance for aerial spraying where the presence of a crossflow is the rule. The first one is that the correlations 3g from Ingebo (1981) might have general validity as it seems to apply to both jet and sheet disintegration in a crossflow. This last statement is based on a limited set of data and requires further support. The other significant result is that the drop diameter spectrum of sprays generated under the influence of strong aerodynamic effects appear to be well represented by distribution functions such as the chi-square distribution for jet atomization and the Nukiyama-Tanasawa function for the break up of liquid jets and sheets in a crossflow. Note that the final drop size distribution will be affected by other processes such as coalescence and evaporation and that the spectrum at the nozzle discussed here can differ significantly from the size spectrum at the target. The implications of these two results are that when aerodynamic effects dominate the break up:

- increasing the surface tension and/or the viscosity of a liquid increases the mean droplet size;
- from the knowledge of the mean droplet size, one can predict the whole drop size spectrum.

Note that with respect to surface tension the situation is reversed when compared to break up in the absence of significant aerodynamic effects where an increase in surface tension is accompanied by a decrease in the mean droplet size.

The viscosity of liquids can be significantly modified by use of the so-called thickening agents. The range of viscosities that can be obtained is large compared to the possible variation in surface tension. This is why viscosity is practically the only fluid property that can have a significant effect on drop formation. Furthermore as we have discussed previously a high viscosity inhibits the formation of satellite droplets thus reducing the amount of very small drops in the 10-50 microns range and contributing to drift reduction.

In a given situation the role of the physical properties in the production of sprays has to be weighted against the role of other parameters, the most important being the orifice diameter (or any significant characteristic dimension), the flowrate and the relative air-liquid velocity. For example in the first eqution of Equation 3g the relative velocity is the dominant term. As is well known the relative velocity can be changed by simply tilting the nozzle relative to the airflow. From a correlation like 3g we see that the mean drop diameter can be varied by changing either the orifice diameter or the relative velocity or the fluid viscosity or the surface tension or all of them. Each situation should dictate the most logical choice for the variable one should modify in order to alter the drop size spectrum. In aerial spraying considerations about the impaction and retention of the drops at the target should influence this choice.

APPENDIX

Derivation of Equation 3c

To derive Equation 3c we start with the dispersion relationship for a viscous jet in a vacuum (Sterling (1969)):

$$\beta^2 + \frac{3}{\mathrm{Re}}\,\beta\,k'^2 = \frac{1}{2N\mathrm{We}}\,(k'^2 - k'^4) \qquad \text{(A-1)}$$

Solving Equation A-1 for k′ we get:

$$k' = \frac{1}{\sqrt{2}}\left[\left(1 - \frac{6N\mathrm{We}\beta}{\mathrm{Re}}\right) \pm \sqrt{\left(\frac{6N\mathrm{We}\beta}{\mathrm{Re}} - 1\right)^2 - 8N\mathrm{We}\beta}\,\right]^{1/2} \qquad \text{(A-2)}$$

We are interested in the intersection of the curve described by Equation A-2 and the curve:

$$\beta = a\,\beta_{opt} \qquad \text{(A-3)}$$

where β_{opt} is given by Equation 3b. Substitution of Equations A-3 and 3b in Equation A-2 yields:

$$\sqrt{2(\Gamma + 1)}\,k' = \left[\Gamma + 1 - a \mp \sqrt{(\Gamma + 1 - a)^2 - a^2\Gamma^2}\,\right]^{1/2} \qquad \text{(A-4)}$$

where $\Gamma = \sqrt{\frac{2}{9}}\,\frac{\mathrm{Re}}{\sqrt{N\mathrm{We}}}$

The ± sign indicates that Equation A-4 has two solutions, one for the intersection at a wavenumber larger than the optimum wavenumber (+ sign) and the other one for the intersection at a wavenumber smaller than the optimum wavenumber (– sign). Therefore the wavenumber range is defined by:

$$\sqrt{2(\Gamma + 1)}\,B = \left[\Gamma + 1 - a + \sqrt{(\Gamma + 1 - a)^2 - a^2\Gamma^2}\,\right]^{1/2} - \left[\Gamma + 1 - a - \sqrt{(\Gamma + 1 - a)^2 - a^2\Gamma^2}\,\right]^{1/2} \qquad \text{(A-5)}$$

Squaring both sides of Equation A-5 yields after some reduction:

$$B = \sqrt{1 - a} \qquad \text{(A-6)}$$

which is the desired result.

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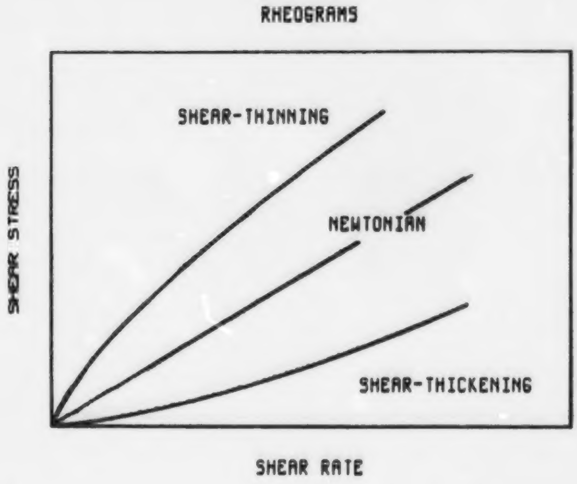


FIGURE 1: TYPICAL RHEOGRAMS FOR SOME BASIC FLOW BEHAVIOURS

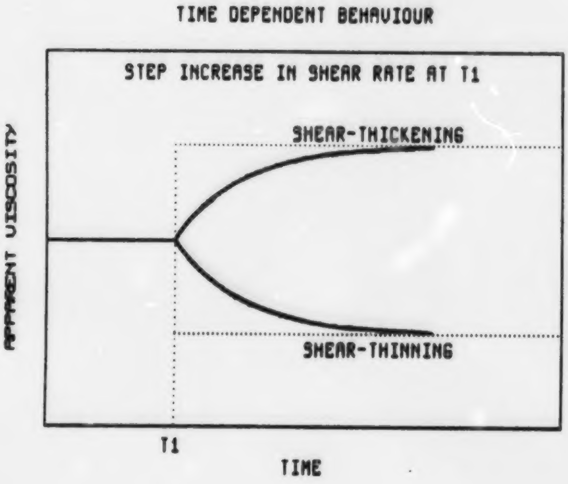
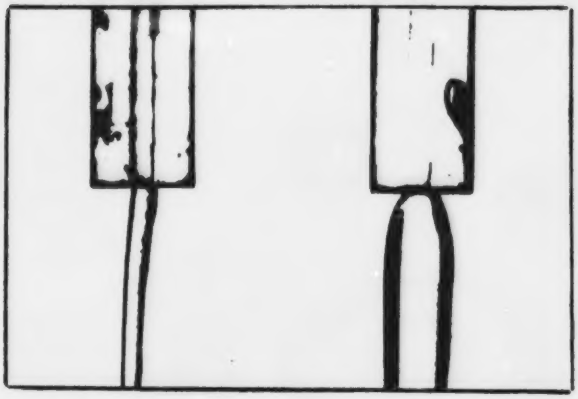


FIGURE 2: ILLUSTRATION OF THE TIME-DEPENDENT BEHAVIOUR



Newtonian
Viscoelastic

FIGURE 3: JETS OF NEWTONIAN AND VISCOELASTIC FLUID ISSUING FROM A TUBE (BRODKEY (1967))

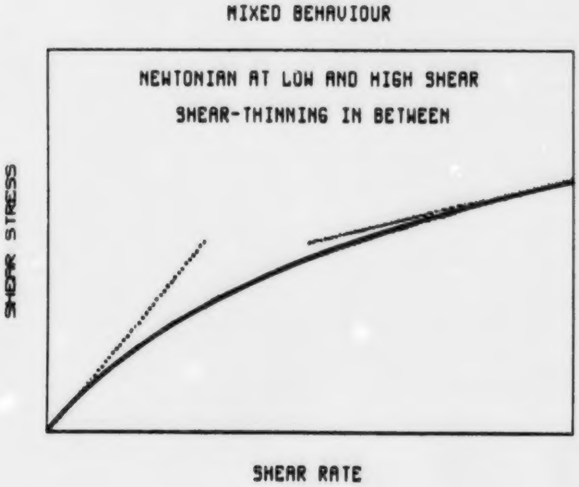


FIGURE 4: ILLUSTRATION OF THE SHEAR-THINNING-NEWTONIAN MIXED BEHAVIOUR

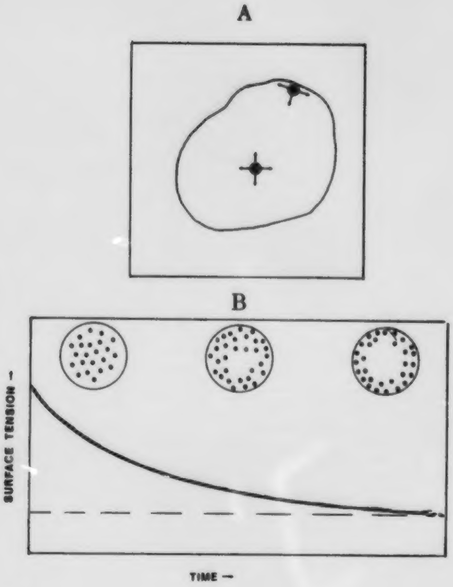


FIGURE 5: A – SURFACE TENSION AT THE MOLECULAR LEVEL. B – DYNAMIC SURFACE TENSION: SURFACE TENSION DECREASES AS THE SURFACE ACTIVE AGENT (DOTS) MIGRATES TO THE SURFACE.

Instability of a liquid jet

FIGURE 6: BREAK UP OF A NEWTONIAN CYLINDRICAL LIQUID JET IN THE AXISYMMETRICAL MODE

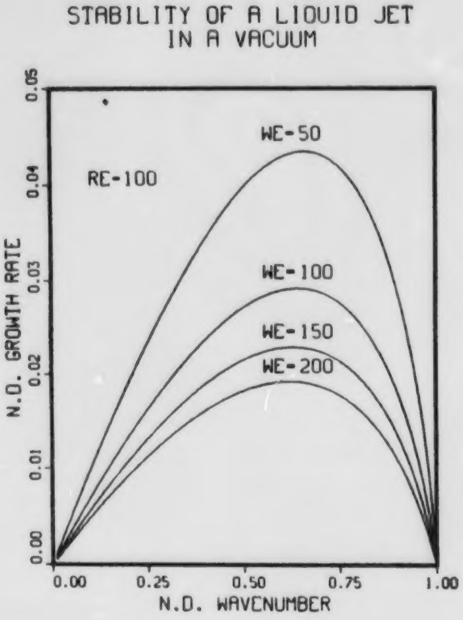


FIGURE 7: EFFECT OF THE WEBER NUMBER ON THE STABILITY OF A JET OF NEWTONIAN FLUID

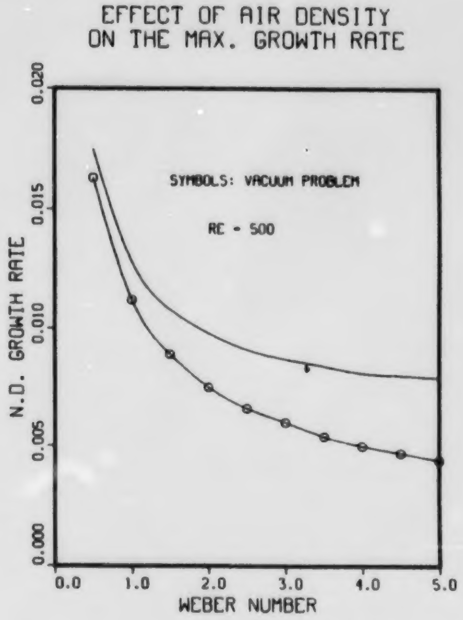


FIGURE 9: EFFECT OF THE WEBER NUMBER ON GROWTH RATE – JET IN A GAS

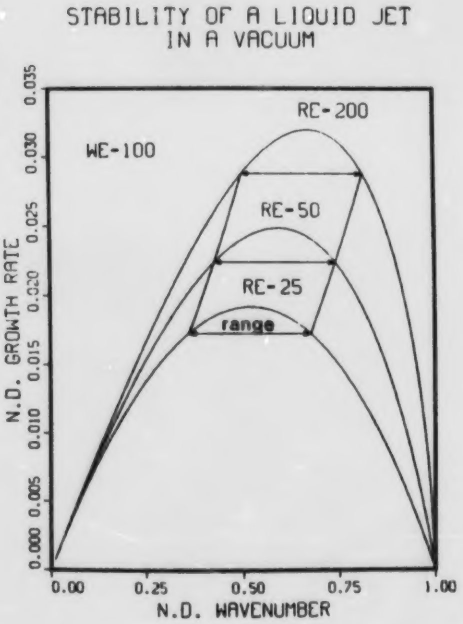


FIGURE 8: EFFECT OF THE REYNOLDS NUMBER ON THE STABILITY OF A JET OF NEWTONIAN FLUID

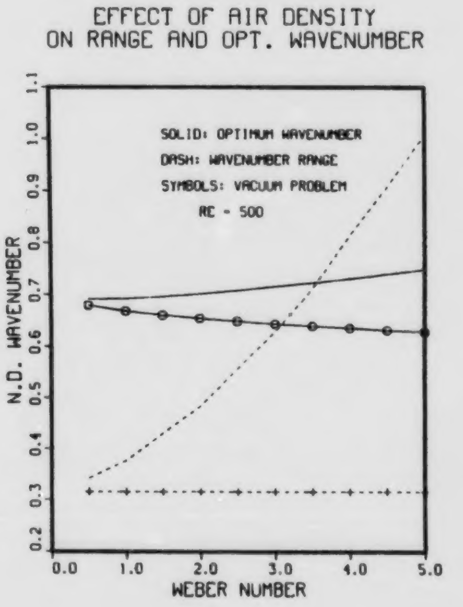


FIGURE 10: EFFECT OF THE WEBER NUMBER ON THE OPTIMUM WAVENUMBER AND THE DISPERSION – JET IN A GAS

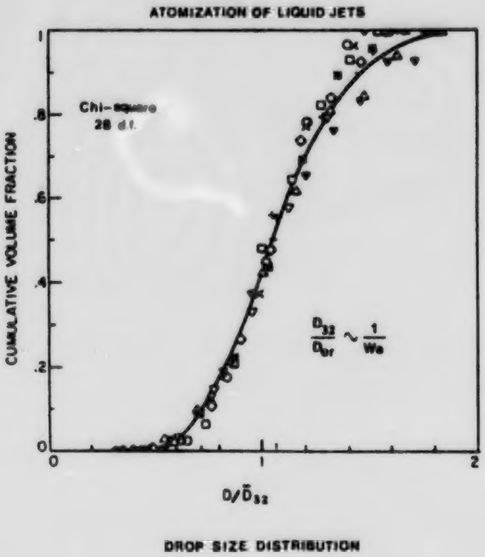


FIGURE 11: DROP DIAMETER DISTRIBUTION FROM THE ATOMIZATION OF A NEWTONIAN LIQUID JET (WU (1986))

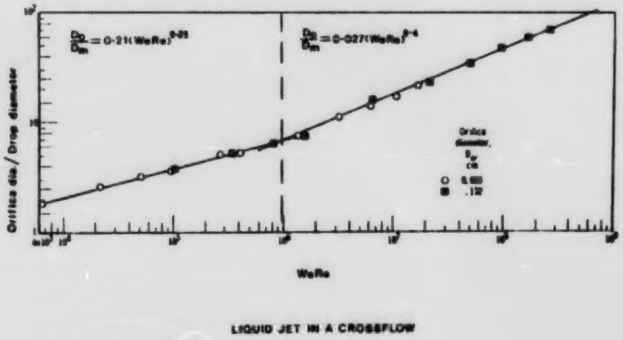
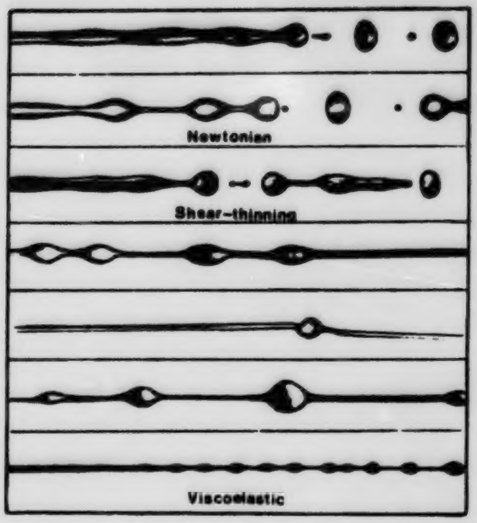
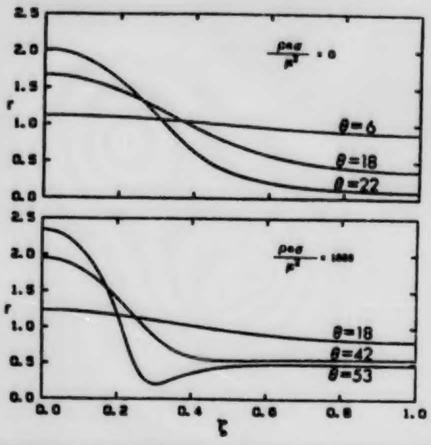


FIGURE 12: VARIATION OF THE MEAN DROP DIAMETER (D_m) WITH WeRe-NEWTONIAN FLUID (INGEBO (1981))


Newtonian
Shear-thinning
Viscoelastic

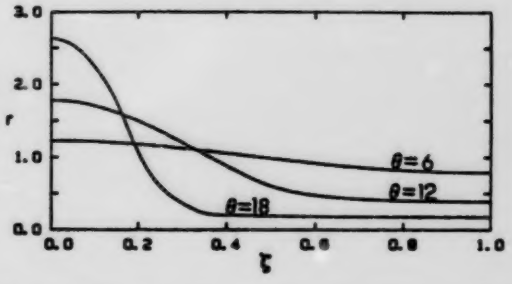
FLUID BEHAVIOUR AND JET BREAK UP

FIGURE 13: FLUID BEHAVIOUR AND JET BREAK UP (GOLDIN (1969))



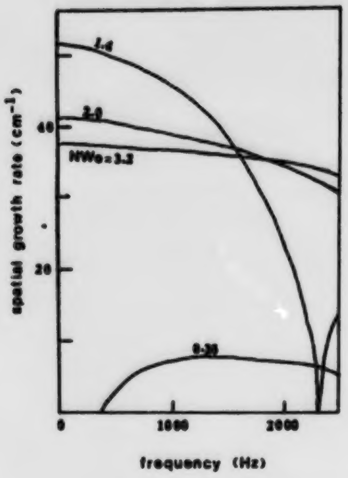
MECHANISM OF SATELLITE FORMATION

FIGURE 15: NUMERICAL SIMULATION OF THE WAVE GROWTH ON NEWTONIAN JETS (BOUSFIELD (1984))



WAVE GROWTH ON A MAXWELL FLUID FILAMENT

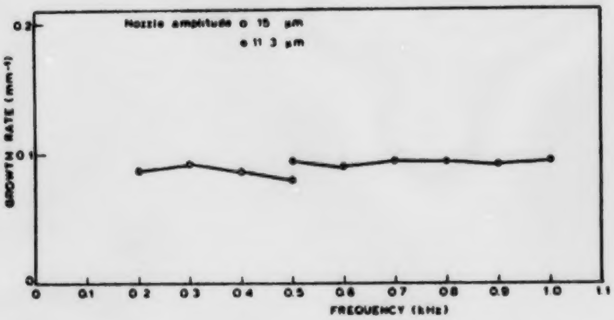
FIGURE 14: NUMERICAL SIMULATION OF THE WAVE GROWTH ON A VISCOELASTIC JET (BOUSFIELD (1984))



STABILITY OF LIQUID SHEETS

GROWTH RATE VS FREQUENCY

FIGURE 16: DISPERSION RELATIONSHIP FOR SHEETS OF NEWTONIAN LIQUIDS (CRAPPER (1975))



VARIATION OF GROWTH RATE WITH FREQUENCY (slit nozzle)

FIGURE 17: EXPERIMENTAL DATA FOR SHEETS OF NEWTONIAN LIQUIDS (CRAPPER (1984))

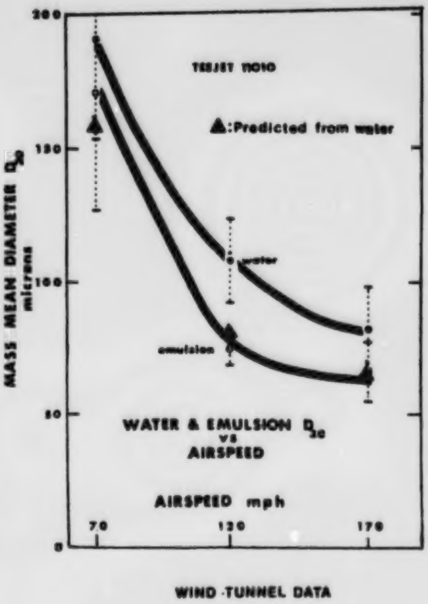
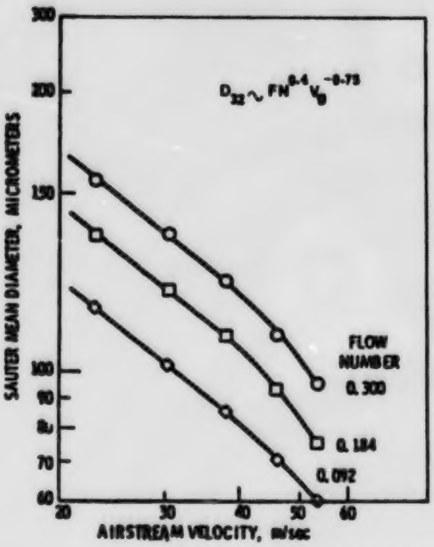


FIGURE 18: MASS MEDIAN DIAMETER AS A FUNCTION OF THE CROSSFLOW VELOCITY (TOMNEY (1978))



Variation of Sauter mean diameter with airstream velocity for pressure-atomizing nozzles.

FIGURE 20: SAUTER MEAN DIAMETER VERSUS AIRSTREAM VELOCITY AT VARIOUS FLOW NUMBER FOR A SIMPLEX NOZZLE (INGEBO (1977))

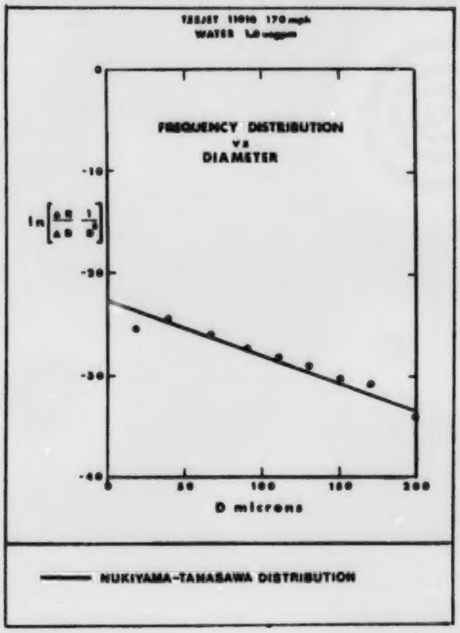


FIGURE 19: DROP DIAMETER DISTRIBUTION FOR A TEEJET 11010 NOZZLE IN A CROSSFLOW (TOMNEY (1978))

IMPROVEMENTS REQUIRED IN SPRAY DROPLET FORMATION TO IMPROVE APPLICATION TECHNOLOGY

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Cranfield Institute of Technology

ABSTRACT — Methods of getting spray to feeding larvae within forests and to adult moths in flight are considered as examples of assessing the application technology required for attacking forest pests. It is concluded that non-volatile droplets between 15 μm and 35 μm in diameter should be sprayed sequentially using the wind to enhance swath width. Results from operations in Scotland and Canada are given to support this conclusion.

The capability of existing types of atomisers to emit their output in droplets in the size range 10 μm - 40 μm is analysed. It is found that the Micron X-1 and the Rotanet atomisers are capable of emitting about 30% of their output in this size range; The Micron X-15 about 23%. Most atomisers generate droplets significantly larger than the size range desired.

It is concluded that a far higher percentage of the emitted spray should be in the desired size range if application times are to be minimised and chemical is not to be wasted. To achieve this, rotary atomisers turning at high speed are required. A detailed analysis of the fluid behaviour in such devices is leading to the design of novel types of atomisers at Cranfield.

RÉSUMÉ — On étudie des méthodes permettant à l'aérosol d'atteindre les larves qui se nourrissent dans les forêts ainsi que les mites adultes en vol en tant qu'exemples servant à l'évaluation de la technique d'épandage nécessaire pour attaquer des ravageurs forestiers. Selon cette étude, il faut procéder à des épandages séquentiels de gouttelettes non volatiles ayant un diamètre compris entre 15 μm et 35 μm, en se servant du vent pour augmenter la largeur de balayage. Les résultats obtenus lors d'opérations effectuées en Écosse et au Canada sont donnés pour appuyer cette conclusion.

On analyse la capacité des types existants d'atomiseurs d'émettre des gouttelettes dont la dimension est dans la plage de 10 μm-40 μm. D'après les résultats obtenus, environ 30 % des émissions des atomiseurs Micron X-1 et Rotanet tombent dans cette plage et environ 23 % de celles du Micron X-15. La plupart des atomiseurs produisent des gouttelettes beaucoup plus grosses que celles souhaitées.

Les auteurs concluent qu'un pourcentage beaucoup plus élevé des émissions devrait avoir les dimensions souhaitées pour que les temps d'épandage soient réduits au minimum et qu'aucune substance chimique ne soit gaspillée. Pour ce faire, il est essentiel de se servir d'atomiseurs rotatifs ayant une grande vitesse de rotation. Une analyse détaillée du comportement des fluides dans ces dispositifs, qui est en cours à Cranfield, amènera la conception de nouveaux types d'atomiseurs.

INTRODUCTION

To improve application technology one must first define the conditions and objectives of pesticide applications. The objective is to deliver, in a cost effective way, the required lethal amount of pesticide to the biological target at the most appropriate time with the least interference to non-target organisms. The conditions assumed are pests in a large forest environment in which it is difficult operationally to select the positions of friends from foes and consequently the specific selectivity of the pesticide is far more important that its absolute toxicity. Considerations of the type and selectivity of the pesticide and the timing will be discussed by other speakers, this contribution will consider the effectiveness of the spray in controlling the damage caused by pests such as spruce budworm larvae, *Choristoneura fumiferana* (Clements). Two different targets will be considered, firstly the larvae and the needles on which they move and feed and secondly the adult moths in flight.

THE LARVAE AS THE TARGET

Whilst it is known that the pests are likely to be in the more vigorously growing parts of the trees their exact positions are not known so a spray technique which gives all likely target surfaces an equal probability of collecting spray is desirable.

It can be shown that in a random system the fraction of the total surface area covered by the spray can be expressed as

$$f = 1 - e \frac{kd^2n}{A} \qquad (1)$$

where f = fraction of the total area which is covered.

k = constant depending upon the spread factor of the droplet.

d = droplet diameter, m.

n = number of droplets.

A = total target area of droplets, m^2.

The exponential form allows for the probability of drops landing in the same position. In forest spraying the fraction of total needle area which is covered by spray is very small, for example 100 droplets of 100 μm spread diameter per square centimeter cover only 0.8% of the surface.

For such a low cover e $\frac{kd^2n}{A}$ approximately equals 1 - $\frac{kd^2n}{A}$ and so

$$\frac{df}{dn} = \frac{kd^2}{A} \qquad (2)$$

i.e. no overlap of droplets.

and hence

$$f = \frac{kd^2n}{A} \qquad (3)$$

By halving the diameter of a droplet the cover will reduce to a quarter of the initial value for the same number of droplets and spread factor. However, for the same volume there will be 8 times the number of droplets so the cover will be doubled for the same sprayed volume.

Not only will the cover be increased by spraying the same volume in smaller droplets, the evenness of the cover will increase. This is fairly obvious if one considers the problem of covering a tray of newly planted seeds: a much more even cover is obtained by using a handful of find dry sand than the same mass of bigger lumps of earth. One fist-sized clod would be useless.

If there is an equal probability of each droplet reaching each target surface then simple probability theory says that the droplets will have a Poisson distribution over the targets. Thus

$$F = \frac{e^{-m} m^r}{r!} \qquad (4)$$

where F is the fraction of the total number of targets on which r droplets land and m is the average number of droplets per target. r! is the product of r with all the integer numbers between it and unity, i.e. factorial r.

Suppose the amount of foliage eaten by a larvae during the active period of a stomach poison insecticide is x square centimetres, or alternatively x is the area crawled over by the larvae if a contact insecticide is being used. Then the number of targets can be thought of as the total insect infected area of surface divided by x. If the insecticide is sprayed in such a size that on average only one droplet lands in x square centimetres, equation (4) can be used to show that it is most probable that 37% of the target areas will not receive a droplet and 26% will receive two or more. Thus no matter how powerful or concentrated the formulation a maximum of 63% of the target areas can be protected. Figure 1 shows the percentage of the total number of targets which are most likely to have at least the specified fraction of the average number of droplets per target. For example when the average number of droplets per target is 2 then 86.5% of the targets would have at least one drop and 32.5% would have three or more drops. If the average number of droplets was increased to 20 then 99.5% of the targets would have at least 10 droplets and only 2.1% more than 30 droplets. Thus if the concentration of active ingredient were such that the average number of droplets per target carried twice the lethal dose then by dividing the spray fluid into sufficient droplets to give an average of 20 drops per target 99.5% of the targets would receive at least an LD-50 dose whilst only 2.1% would have three or more LD-50 doses. This argument is developed further in another paper (Spillman 1980).

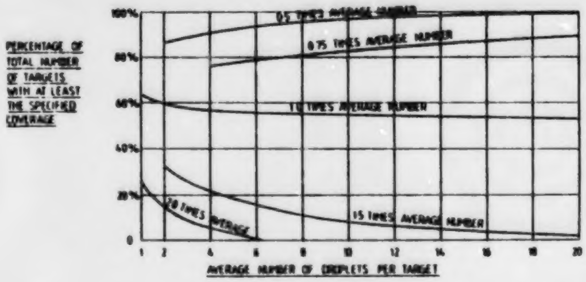

FIGURE 1: EFFECT OF AVERAGE NUMBER OF DROPLETS PER TARGET ON PERCENTAGE TOTAL COVERAGE

The argument above is essentially about droplet numbers not concentration. The size of the droplet must be such that the required amount of pesticide can be carried satisfactorily in it. This is unlikely to be a problem since by decreasing the size of droplet for a given total amount of spray decreases the concentration of active ingredient required to put an LD-50 dose on a specified high fraction of the targets. For example Fig. 1 shows that with only 4 droplets per target the four droplets between them must carry two lethal doses for 90% of the targets to get at least one lethal dose. With 20 droplets per target having the same total volume they need carry only 1.5 lethal doses between them to give an LD-50 dose on 90% of the targets.

Difficulty in concentration will arise only when particulate formulations are used because then small droplets may not have proportionate numbers of grains or crystals. In general the desire for low concentration to maximise the uptake of the active ingredient by the target does not conflict with the desirability for a large number of small droplets. It follows that the smallest droplet associated with acceptable capture efficiency and biological efficiency is desirable for best cover.

Many investigators, (e.g. Barry et al 1977, and Himel and Moore 1969) have shown that the optimum size of droplet caught by larvae and coniferous needles is in the range 20 μm to 50 μm, the smaller sizes probably being better if they can carry a satisfactory amount of active ingredient. With droplets of this size, wind has a great effect in distributing them evenly over and around the foliage by turbulent diffusion. Indeed wind is the essential mechanism whereby the droplets are spread out from the atomiser to give a near even distribution on the foliage. Without wind, the turbulent mixing of the air will be negligible and the droplets will stay in relatively dense clouds falling very slowly and being blown in an undirected way by the odd puff of air which arises occasionally. In other scenarios this has been the cause of severe off-target damage (Watt 1980).

It has been shown that evenness of cover with small droplets is obtained best by using an incremental drift spraying technique, using the wind to drift the spray downwind and overlapping the deposits, ideally both in time and space although sequential spraying may increase the operational costs (Joyce 1976).

It would seem that the best application procedure against larvae is to drift spray the formulation in the smallest droplets which can carry a useful amount of active ingredient. However, two other factors have to be considered. Firstly, small droplets evaporate rapidly if of a volatile nature and it is imperative that this should not happen since too small droplets would not be captured sufficiently well and might become so concentrated as to be phytotoxic. Comparative trials of oil and water based formulations with the same active ingredient, have shown that the size of the water based spray droplets arriving in the target area was significantly smaller for the water based spray than for the oil based formulation (Cadogan 1986). In the first application the volume median diameter of the droplets arriving at the target area was 45 μm for the water based formulation and 104 μm for the oil based one. In the second application the values were 33 μm and 99 μm respectively. The overall larval mortality was 84% for the waterbased formulation and 85% for the oil based one. Had the oil been atomised into the same droplet size spectrum as that of the water formulation on arrival at the target surfaces then the spraying times of the aircraft per sortie could have been increased to 12.3 and 27 times respectively because of the lower rate of emission required! These increases are huge compared to the penalty of spraying the same area twice at the same total application rate which would almost certainly have increased the mortality.

Some work on evaporation at Cranfield has suggested that the evaporation of water based sprays can be significantly reduced by adding molasses. (Spillman 1984). This might prove to be a cost effective way of minimising the effects of evaporation.

A second consideration is that small droplets may not be caught readily by the target surfaces. However, while too low a capture efficiency means that the droplets drift considerable distances from their emission points, too high a capture efficiency means that most of the droplets are caught by the first surface they encounter and are unlikely to penetrate sufficiently into the canopy. Figure 2 illustrates this effect. Clearly the lower the capture efficiency the more even the distribution of spray amongst the targets but the lower the average deposit. It is probable that a capture efficiency of between 30% and 50% is desirable; since the third to fifth target is collecting at least 25% of the deposit level of the first target.

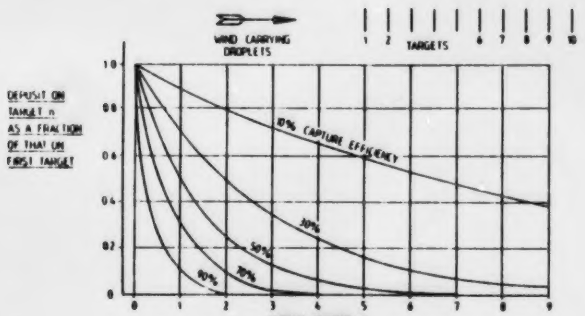

FIGURE 2: EFFECT OF DROPLET CAPTURE EFFICIENCY DOWNWIND DISTRIBUTION OVER TARGETS

If one considers a ribbon or cylinder 2 mm wide, corresponding to a larva or a needle, then a catch efficiency of 40% corresponds to a relative wind speed of 1 m/s for droplets 19 μm in diameter, to 0.5 m/s for droplets 29 μm in diameter, 0.25 m/s for droplets 41 μm in diameter and to only 0.1 m/s for droplets of diameter 70 μm. This is the range of wind speeds most likely to be found in the outer parts of the canopy at the biologically correct time for spraying the forests bearing in mind that some wind is desirable to give adequate turbulent dispersal to the spray. The droplet size range corresponds well to that found to be optimum by Barry et al. and Himel and Moore.

It was arguments similar to those given above which were used in planning the spray programme in 1978 to protect the lodgepole pine forests in Scotland against damage by the larvae of the Pine Beauty Moth *Panolis flammea* D&S, family *Noctuidae*. (Joyce et al. 1978). This operation is of particular relevance to the arguments advanced in this paper because two spray techniques were used and compared. As no approval for an ultra-low volume spray programme existed, only part of the forest was sprayed in the recommended way, the rest was done using the low volume spraying technique which was then the only approved method. The results are summarised in Table 1. It is important to note that during the ultra-low volume spraying the wind was 7-8 knots on the first day increasing to 13 knots on the second day, conditions which ensured a neutral atmosphere and a high level of turbulent dispersion near the forest canopy. Inspite of these high winds the measurements of the independent monitoring organisations suggest that only 1% of the spray was lost outside this long, narrow block.

The results show that both the U.L.V. and L.V. sprays gave a 97.5% larvae mortality, and the average amount of chemical found in the dead larvae in the U.L.V. trial was at least three times that required for this percentage mortality. The lower application rate made the efficiency of the system much higher than that for the low volume application. Droplet sizes impacting on the canopy were mainly in the size range 20-50 μm in diameter.

Subsequently other trials have shown similar requirements for effective larval spraying in coniferous forests. (Cadogan 1986 and Cadogan et al 1986).

THE FLYING MOTH AS THE TARGET

Radar observations have shown that moths migrate in quite dense formations over Canadian forests and that the moths are concentrated by weather fronts as they fly downwind. (Schaefer 1979 and Greenbank et al 1980.) Samples of the flying insects have been caught using an airborne net and shown to be almost exclusively spruce budworm moths. Calculations based on the work of Lawson (1976) and Spillman (1976) have shown that very small amounts of pesticide are required to kill clouds of flying insects provided droplet sizes are all in the range of 15-25 μm and the formulation is non-volatile. The empirical estimates of the efficiency with which these small droplets are caught by the various parts of the insects exposed during flight has been confirmed by some very careful windtunnel tests on flying house flies, *Musca domestica*, and Egyption cotton leafworm moths, *Spodoptera littoralis* (Gadalla 1984). He showed that in flight both types of insects caught more spray on their wings than on any other part of their bodies, of the order of 50% by the house flies and 70% by the moths. Clearly an insecticide which is effective when caught on the wings is desirable. The heads of the insects caught only about 25% and 13% respectively for flies and moths. The overall catch efficiencies increase from 33% and 22% respectively for droplets of 20 μm in diameter to 54% and 45% for 80 μm droplets.

However, when the effects of airborne time and air turbulence are considered, as suggested by Spillman (1976), the optimum droplet sizes become 22 μm and 27 μm for the flies and moths respectively.

It follows that droplets in the size range 15 μm - 35 μm diameter are required for spraying against both the larvae and the flying adults. If adequate control of droplet size is to be obtained the formulation used must not be volatile to any significant degree.

AVAILABLE ATOMISERS

The conclusion to be drawn from the above analysis is that aerial spraying against insect pests of forests requires atomisers which will make droplets in the size range 15 μm - 35 μm from non-volatile formulations. Assuming a droplet density of 25 droplets per square centimetre of leaf surface, a leaf area/ground area ratio of 5, an aircraft flight speed of 60 m/s and a lane separation of 100 m, the emission rates required are about 0.8 to 10 l/minute for this size range. If the droplets were all 25 μm in diameter 450 billion droplets per minute are required, giving a total flow rate of only 3.7 l/minute. Clearly there needs to be careful control of the size of droplet into which the formulation is atomised. If the upper limit of the specified size range is too high the number of droplets per litre will decrease dramatically. If the lower limit is too low, their catch efficiency and capability of carrying an effective dose will be poor. If the size range is too narrow the possibility of achieving a reasonably high fraction of the spray emitted in the desired size range will decrease significantly. It will be assumed for the sake of comparison in this paper that droplets of 25 μm ± 15 μm are the ones desired and that the percentage of the total volume in sizes between 10 μm and 40 μm is a measure of the efficiency of the atomiser. At the same time each atomiser should have a flow rate of at least 0.3 l/minute and preferably above 1.0 l/minute.

Results from tests made by the International Centre for the Application of Pesticides at Cranfield in their spray tunnel using a P.M.S. laser beam droplet sizing probe on various kinds of aircraft atomiser are shown in Table II. The results for the 11006 nozzle and the Bifoil come from Parkin and Newman (1977), the others from various private communications. The results for the Micron X15 are made available by the courtesy of the Forestry Commission of Great Britain. The results are for a formulation of water and surfactant. This tends to give somewhat smaller droplet sizes than more viscous formulations.

TABLE I

Type of application	Ultra-low volume application	Low volume application
Formulation	6 Parts Fenitrothion 50 EC 4 Parts Butyl Dioxytol	3 Parts Fenitrothion 50 EC 97 Parts Water
Atomiser	Two Micronair AU 3000 Standard 5" Cage, 13.5" Flat Blades Set at 25°	Six Micronair AU 3000 Standard 5" Cage, 13.5" Flat Blades Set at 25°
Application Rate	1 Litre/Ha	20 Litres/Ha
Active Ingredient Rate	0.3 Litre/Ha	0.3 Litre/Ha
Release Height Above Canopy	6 m	3 m
Lane Separation	50 m (Two Applications at 100 m on successive days)	25 m
Emission Rate	15 L/min	150 L/min
Droplet Sizes	vmd 97 nmd 24	vmd 104.5 nmd 22
% of volume between 10 μm and 40 μm	8.0%	8.4%
Spraying Speed	180 km/hour (50 m/s)	180 km/hour(50 m/s)
Wind Speed	7-8 knots day 1 13 knots day 2	1-6 knots
Area Sprayed	50 Ha (2 km by 250 m)	100 Ha
Ferry Distance	100 km	30 km
Overall Work Rate	309 Ha/hour	88 Ha/hour
Destination of Active Ingredient		
a) Collected by needles or larvae	94.5%	41.7%
b) Lost to ground within block	4.5%	38.3%
c) Lost outside block	1%	20%
Average Larval Weight	28 mg	108 mg
Mean Deposit on 20 needles	41.2 ng	23.6 ng
Mean Deposit on Single buds	18.8 ng	23.6 ng
Mean Deposit on Larvae per gramme of larval weight	1285 ng/g	407 ng/g
Mortality	97.5	97.5

TABLE II: Atomiser Characteristics

Atomiser		Test Condition	Pressure KPa	Rotational Speed R.P.M.	Orientation or Blade Setting	Flow Rate Litres/ min	v.m.d. µm	n.m.d. µm	v.m.d./n.m.d.	% Volume in range 10–40 µm
HYDRAULIC NOZZLES	80015	113 knots	276		45°	0.57	154	58	2.64	0.62
	80015	113 knots	1380		45°	1.03	119	50	2.38	1.2
	110015	113 knots	276		45°	0.57	152	59	2.58	0.65
	11006	113 knots	276		45°	2.4	115	35	3.29	3.0
	BIFOIL	113 knots	113		180°	12.0	82	20	4.10	9.5
ROTARY CAGES	MICRONAIR	13.5" Flat Blades				7.5	97	24	4.07	8.0
		5" Cage								
	AU 3000	100 knots				24.0	104	22	4.70	8.4
	ROTANET	11" Twisted Blades	113 knots	11000	25°	2.5	51	19	2.67	30.1
		5" Cage								
		13.5" Flat Blades	95 knots	6600	30°	10.0	112	31	3.61	4.3
ROTARY TOOTHED AND GROOVED CUPS	MICRON X1	97 knots		8200		0.05	38	22	1.7	54.0
						0.1	42	25	1.65	43.0
						0.2	51	30	1.7	27.0
						0.4	75	37	2.0	9.5
						0.8	91	35	2.6	6.0
	MICRON X15			4300		1.6	120	35	3.4	3.0
				6000		0.6	100	28.1	3.35	3.6
				6000		1.2	106	28	3.85	3.5
				6000		1.8	106	25	4.26	4.1
				12000		0.6	66.8	24	2.78	16.8
				12000		1.2	78.1	24	3.25	11.1
				12000		1.8	82.2	24.3	3.38	9.6
				14000		0.6	60	23.6	2.54	22.7
				14000		1.2	71.9	23.3	3.09	14.9
				14000		1.8	78.3	23.5	3.33	12.1

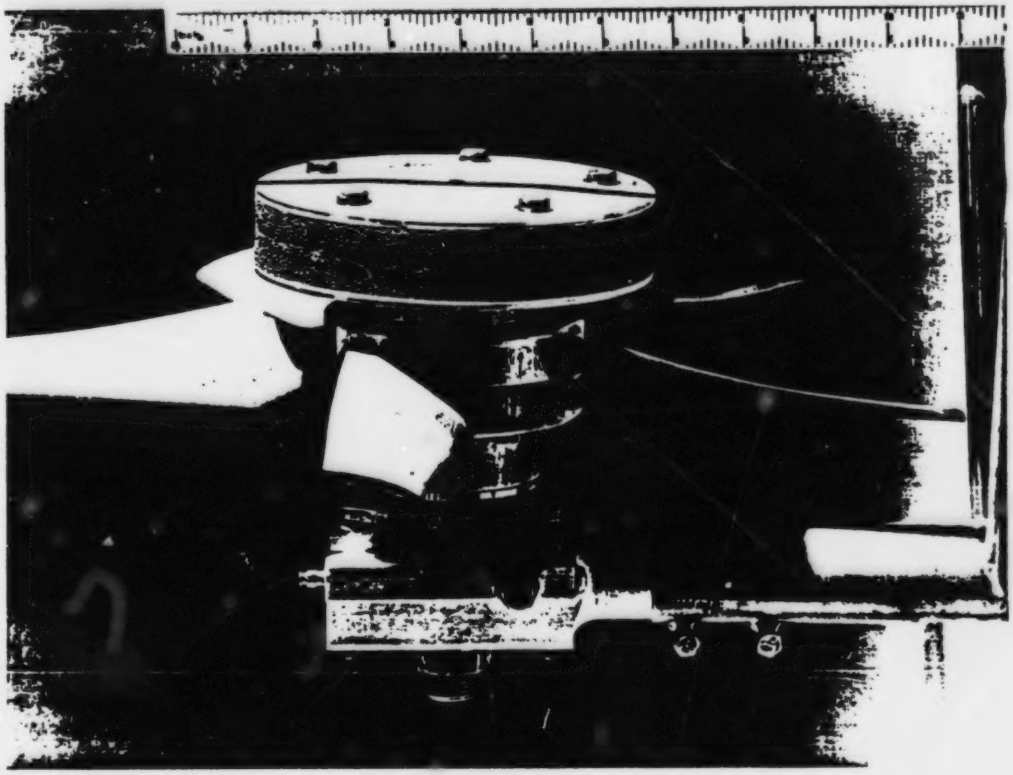

FIGURE 3: The Rotanet Atomiser

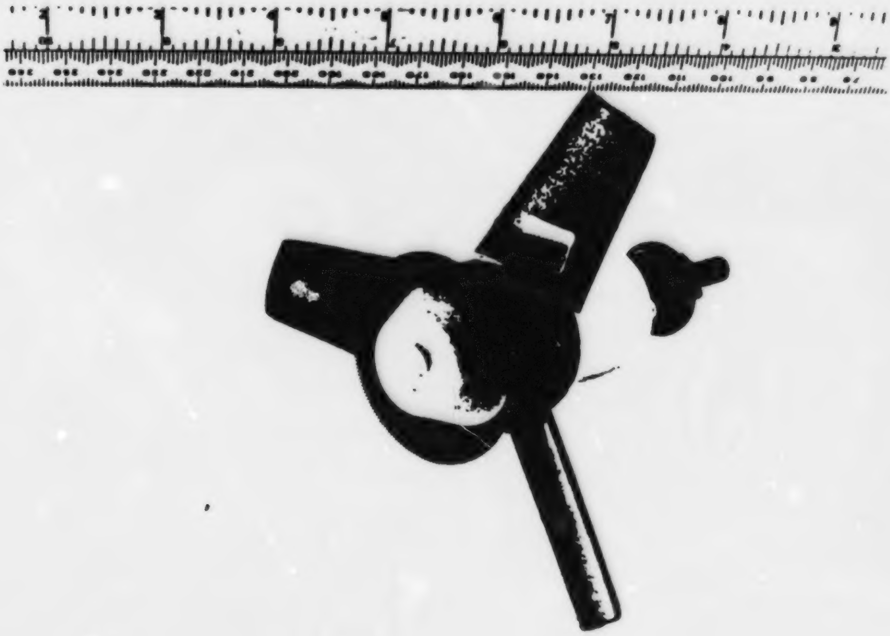

FIGURE 4: The Micron X-1 Atomiser

The hydraulic nozzles show a very low percentage of the emitted volume in the size range desired. This is not so much that the width of the size spectrum is large, indeed results have been chosen for cases where the v.m.d./n.m.d. ratio is surprisingly low for hydraulic nozzles, it is because the droplet sizes are too large, inspite of the small nozzle hole size. Increasing the pressure to 1380 kpa (200 lb/in^2) gives a slight improvement but is not sufficient to generate the droplets in the right size range. A twin fluid nozzle is required for this, and the Bifoil, is essentially this as the small hydraulic nozzles spray into the venturi throat of the device where the larger droplets are shattered into smaller ones by the locally high air velocity. Inspite of the rather large v.m.d./n.m.d. ratio almost 10% of the volume emitted is in the desired range of sizes and the ten nozzles per device give an overall flow rate of 12 litres/minute.

The more carefully controlled atomisation processes of the rotary cage devices give much better results than the hydraulic nozzles particularly when set to give high rotation speeds. The 30% ratio of volume in the desired range from the Rotanet was limited by reaching the maximum speed of rotation at which an acceptably low level of vibration could be maintained. It is clear that at lower rotational speeds and higher flow rates the performance reduces significantly.

The Micron X-1 single cup atomiser and the multi-cup X-15 both give good results. The X-1 giving over 50% of the emitted volume in the desired range of sizes, but unfortunately only at the very lowest flow rate. If the rotational speeds could be increased then similar results might be obtained at higher flow rates. The X-15, with its fifteen cups, when driven at 14000 r.p.m. does achieve almost 23% of its emitted volume in the desired size range for a flow rate of 600 ml/minute.

Of the existing atomisers it would seem that by fitting 40 X1 atomisers, application rates of 2 l/min could give over 1 litre/min in droplets in the 10 μm to 40 μm range. Alternatively for an emission rate of 8 l/min almost the same amount of fluid would be in the same size range, the rest being in somewhat bigger droplets.

One Rotanet emitting 2.5 l/min would produce 0.75 l/min in the desired size range, almost all of the rest being somewhat bigger. If the rotational speed could be increased above 11,000 r.p.m. by better balancing of the device it could be extremely attractive. It is probable that this argument applies equally well to the Micronair devices but it may be even more difficult to achieve the rotational speeds needed to get the volume median diameter into the desired range of sizes without excessive vibration or over-stressing of the components.

Thus of the existing devices the Rotanet and the Micron devices seem most attractive. If 450 billion droplets per minute above 15 μm are to be generated then four Rotanets operating at 11,000 r.p.m. and a flow rate each of 2.5 l/min or less would be required. If 50 Micron X-1 were used, a flow rate of 0.2 l/min each would give about the same result at the same flight speed. It is probable that eight Micron X-15 with a flow rate of 1.2 l/min each driven at 14000 r.p.m. would not be quite so successful. In each case a total flow rate of about 10 l/min would be required, compared to an ideal value of 3.7 l/min.

THE WAY FORWARD

It seems clear that in order to get a larger fraction of the spray in the required size range the atomisation process must be a well controlled ligament break-up rather than the random sheet break-up of hydraulic nozzles or the random impact process of wire cages. Thus rotating devices with well formed emitting points seem attractive assuming that blockage problems rule out devices using pulsed jets through very small holes.

It can be shown that in order to make small droplets, the diameter of the liquid filaments from which they are made must be smaller still. It follows that the liquid flowing radially near the perimeter of a grooved and toothed disc or cup must be of only a few tens of microns in thickness. If the flow rate of the atomiser is not to be minute the radial velocity of this liquid must be several metres per second. As a consequence the frictional stress between liquid and the groove surface must be very high, increasing with increase in flow rate or decrease in droplet size required. There is strong evidence to suggest that with some spinning disc atomisers the radial velocity of the fluid on the disc reaches a maximum some distance before the perimeter and subsequently decreases with increase in distance towards the edge of the disc. The only way to increase the driving forces to offset this effect is to increase the centrifugal acceleration and reduce the surface area over which the friction acts.

Arguments like these, arising from an attempt to understand and quantify the physical processes involved in generating a spray of near monosized, very small droplets, are leading the author and other research workers at Cranfield towards novel designs of atomisers. Preliminary trials of these show considerable promise but this must be the subject of another paper.

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SESSION II DISCUSSION PERIOD

Panel Chairman — A.M. Drummond
Panel Members — D.D. Kristmanson, B. Panneton, J.J. Spillman

Chairman to Mr. Panneton:

In his opening address, Dr. Carrow discussed *B.t.* and the withdrawal of the normal insecticides, which I was not aware of and which was a surprising thing to me. Also, of the 29 Poster abstracts that we accepted, fully 9 of them were discussing *B.t.* in the context of the paper. It is my perception that most of the *B.t.* products are non-Newtonian in their stability characteristics. Apparently we will be dealing with *B.t.* a lot more in the future. Could you address the atomization of *B.t.* within the Weber and Reynolds Number concept of your presentation? Also, there is an apparent variability of *B.t.* in controlling spruce budworm. Could this be traced to a variability in the atomization characteristics of *B.t.* or is this something other than at the fluid mechanical level?

Bernard Panneton:

It is my understanding that most *B.t.* formulations are viscoelastic. Both Dr. Kristmanson and Prof. Spillman were discussing very small droplets and talking about very high shear stresses in order to atomize the spray formulation into very fine droplets. The fact that the *B.t.* formulation is shear-thinning or, as others would say, pseudo-plastic, is less relevant with high shear stress spraying devices because, as the shear rate increases, the apparent viscosity of the pseudo-plastic fluid decreases. However, some distance away from the nozzle, all the shear stresses will relax and then the apparent viscosity of the *B.t.* formulation may well rise very quickly thus preventing the formation of the very small drops that are required to achieve good control. This may explain some of the variability observed in the efficacy of *B.t.* formulations in the field. Obviously, this is only part of the answer since adhesion at the target and deposition efficiency as well as all the many biological parameters should affect the process as well.

Jules Picot:

I do have a few pointed comments. We have been working with the eastern spruce budworm problem for the past 12 years and recently we have studied small droplets. In the past, high speed flash photography had been used to correlate droplet size distributions and to measure and count the droplets. Measurements on sub-60 micron droplets at air speeds of 50 to 75 m/s cannot be made with flash photography. You lose a great deal of the small drops. About 1980, we started using laser spectrometers to study droplet emissions and found many small droplets just like you see in the field during droplet capture measurements. Recently, we have become pre-occupied with measurements from high-speed rotating devices to get the small drops, specifically the Micronair AU 4000 operating at 14000 RPM with a low flow rate of 2 l/min. You can get between 75 to 85% of the volume between 15 and 55 microns. None of the correlations explain this. You can be two orders of magnitude in error by trying to calculate the average drop size because the small droplets do not show up on the photographs. The Tomney work from UNB, done in 1978–79 that Dr. Kristmanson showed, is all done with photographic measurements. We have recently published work in the ASAE Journal that, with laser spectrometers, you don't get the same mean or droplet size distribution. I think this conclusion is quite important.

Chairman:

To paraphrase your comments, Dr. Picot, your main point is that the method of taking the data can lead you to potentially incorrect conclusions on the drop spectra.

Jules Picot:

Early correlations published in the literature before the early 1980's were very likely obtained using photographic methods and are probably incorrect, certainly for the mean drop size. For focussing on the cumulative volume fraction distributions, the data are not too bad. In fact most people nowadays are going to that and, as Dave (*Kristmanson*) suggested, they look at the spectrum span and the volume median diameter.

Steve Parkin:

I have a question for Mr. Panneton regarding his statements about *B.t.* We have heard this morning how important *B.t.* is to Canadian forestry. We will be using more of these unusual liquids which are non-Newtonian. In my experience, *B.t.* tends to be a shear-thinning fluid. He quite rightly suggested that there is an apparent viscosity rather than an absolute viscosity because viscosity depends on how much the fluid is stressed. What worries me is that we are not really measuring what happens. Laboratory viscometers treat a fluid very gently. There are no very high shear rates, certainly not the shear rates the liquid is exposed to in an ordinary hydraulic nozzle. As a result, the apparent viscosities we measure are on the order of thousands of centi-poise. Newtonian fluids with such a high viscosity could not get through an ordinary nozzle. The *B.t.* suddenly becomes a thin, low viscosity liquid as it goes through the nozzle. We do not know what viscosity the fluids have as they go through the nozzle. We do not seem to be able to measure the viscosity of fluids at these high shear rates. To understand *B.t.*, we are going to have to understand what is going on at the nozzle with the enormous shear rates present there, because, unless we do that, we won't be able to make any predictions on the effects of viscosity on droplet size which I think is so necessary.

Chairman:

Mr. Panneton, do you have any comments on the shear rate question?

Bernard Panneton:

The only technique that I know of where fairly high shear rates can be generated is to force the fluid through a small tube by simply applying pressure and measuring the flow rate at a given pressure. Now, if you know in advance whether the fluid is shear-thinning or shear-thickening, you can assume the appropriate empirical law to apply and then derive the flow rate versus pressure relationship in terms of the parameters that describe the non-Newtonian behaviour and, from your flow rate versus pressure experiments, you can deduce the values of the main parameters.

John Maybank:

I have 2 questions. The first is to Prof. Spillman. With reference to the last Table you showed, and if we accept for the moment that 25 to 30 microns is the most appropriate drop size in the insecticide situation, could you have a volatile mix and have the spray spectrum evolve to reach that size? I recognize that there are many difficulties to be overcome. My second question is to Dr. Kristmanson. In your slides of size distribution where there was a break between the small size and the large, did you assign responsibility of error to the instrument measuring the larger size? Would you elaborate on that a bit?

John Spillman:

Certainly one can think of using evaporation as a way of getting the drops near the canopy down to the size that I was discussing, but there are two things to bear in mind. The first is that, by definition, anything that does not go to the target and do something useful for biological purposes is waste. Anything that evaporates off is in that category. The second thing is that the rate of evaporation depends very much on the local conditions. For small drops and for drops whose rate of change of diameter is of the order of 1 micron per second, then a relatively small change in flight time will make quite a big range of drop diameters. When the drop is small, we worry about catch efficiency. I think the preferred way of providing a small drop size is to try to keep the formulation non-volatile and try to get the drop size you want coming out of the atomizer.

Dave Kristmanson:

Perhaps I could provide a little more detail on how the measurements were done. We had to make a traverse of samples through the plume left by the atomizer at a representative number of points using 2 devices: The Forward Scattering probe which looks at drops smaller than 50 microns, and the Imaging probe that works at the higher size ranges. After a great deal of effort by Dr. Picot and Mr. Van Vliet, they came to the conclusion that to make the necessary mass balance work, they took the Forward Scattering probe to give an absolute number count. The Imaging probe has an uncertainty about the sampling volume that you are seeing. The Imaging probe gives relative counts rather than absolute counts. The two distributions are matched by forcing the mass balance to close. There are technical reasons why, at the lower end of the Imaging probe's range, it is quite difficult to get a handle on the true number of drops going by. Would Dr. Picot like to elaborate on the subject?

Jules Picot:

The problem with the Imaging probe is that there are too many droplets in our spray for the probe to follow everything. It needs time to do some calculations on its internal computer. For the Forward Scattering probe that happens but it has a circuit that tells you how much time the probe is dead, how much time is spent doing calculations. We use a very well calibrated Scattering probe and we use the mass balance criterion already described. We fit the drop distribution curve and when we see a dip, we understand why. There are many more small drops than there are larger droplets, so we are more faithful in the curve at the larger end. We have some errors and we are quite happy with the situation. We simply, conceptually, put a straight line through that little dip in the curve.

There was something I wanted to say about our work with *B.t.*, Dipel 32. With a rather low shear measurement, you get about 300 centi-poise and with a few reciprocal seconds of shear you went down to 100 or so, very strongly non-Newtonian. But with the AU 4000 rotating at 14000 rpm and 2 l/min of flow you ended up with about 75% of the volume between 15 and 55 microns. If you were to consider another test that we did with a material of around 6 centi-poise, a Newtonian mixture of water and one of the alcohols, we ended up with about 85% in the same size spectrum at the same speed and flow rate. This indicates that the correlations previously discussed would not show this. We don't have ligament or sheet breakup. We have catastrophic shattering of droplets which are being hit by a wire. We still have not analyzed that particular case properly, theoretically.

Alam Sundaram:

I have one question for Dr. Kristmanson and one comment. Then I have a question for each of Mr. Panneton and Prof. Spillman. First, to Dr. Kristmanson. I was intrigued by the high flow rate used in your laboratory of 3.1 USgpm with a relative span of 1.46 for your T-jet nozzles and 2.04 for the Micronair AU 3000 nozzle. The question is, did you use the same flow rate for the Micronair as well because that was not very clear? Did you use the same 1 gallon per minute?

Dave Kristmanson:

(Unfortunately, Dr. Kristmanson's reply was not audible on the tape.)

Alam Sundaram:

That explains why a high relative span of 2 was measured from the Micronair. In our experience of almost 8 years, at 2 l/min, you do not get a high relative span with a Micronair as compared to a T-jet nozzle.

Dave Kristmanson:

How do you measure the drop size distribution?

Alam Sundaram:

It is not how you measure it, but what you get out of the spray at the target. We used gas chromatographic methods to assess the deposit at the target. The upper end of the size spectrum contributes most of the mass. Using a Micronair, at a lower emission rate, you have a much less relative span compared to the hydraulic nozzle.

Dave Kristmanson:

The deposit on the needle won't show all of the small drops that are collected rather inefficiently and drift off target.

Alam Sundaram:

We are not talking about small droplets. We are now talking about the upper end, the DV .9, which is very high.

Dave Kristmanson:

You were talking about the relative span?

Alam Sundaram:

Exactly.

Dave Kristmanson:

You need to know about the small droplets, the DV .1, in order to calculate the relative span.

Alam Sundaram:

If DV .9 is high, obviously the relative span is going to be high.

Dave Kristmanson:

Yes.

Alam Sundaram:

This is theoretically being supported especially liquid breakup. If you emit, like Prof. Spillman pointed out, very high flow rates you are going to end up having some larger drops. He pointed that out too and which we have observed.

Alam Sundaram:

Mr. Panneton, when you use a rotary cage nozzle like a Micronair, there is some evidence, which is being supported by theoretical work in England, that the surface tension of a liquid has little relationship to the drop formation or ligament breakup at the end of the rotary cage.

Bernard Panneton:

If I have understood the question correctly, I think that you have not observed any effect of surface tension on drop size using a Micronair. I think that part of the answer has to do with recent comments of Dr. Picot that the process of fluids going through the Micronair nozzle and being pushed out by a centrifugal force has still to be fully explained. The centrifugal acceleration varies as the fluid moves from cage to cage. This might well hide possible effects of surface tension. It is hard to get a factor of 2 in surface tension between two fluids for experiments. The more complex the process, the more likely it is that the small effects of surface tension will not show up.

Alam Sundaram:

Especially when you use an X-15 nozzle which has a lot of serrations in addition to the rotary force. The liquid atomization is more complex.

John Spillman:

If the flow rate through a Micronair is allowed to rise to a much higher value, then surface tension would become a more important parameter because you would find a different mode of atomization.

Steve Parkin:

I have found that, with a decrease in surface tension, I have measured a decrease in the VMD droplet size between pure water and water with a surfactant at a high flow rate.

Alam Sundaram:

Prof. Spillman, you made an interesting comment. If you want to emit 3.7 l/min through a Micronair and if you want to get a drop spectrum between 15 and 60 microns, you'll have to atomize it rotate it so fast you will need, which is impossible, you will need so many atomizers to be put in the aircraft. Here I would like to make a comment. Unless you have a very long boom where you can separate these atomizers at a comfortable space between them you are going to get larger drops mainly because of droplet coalescence. If you emit a large number of small droplets in a narrow space, a narrow volume of air, they are going to collide with each other and, depending on the fluid properties, there is definite coalescence of droplets. So, unless you have a long boom, the whole technology of spraying needs to be considered very differently. When you change the length of the boom, then you have to change the whole aerodynamics and everything. So, mounting umpteen number of nozzles, to me, it is not the answer. It looks like decrease the flow rate and produce small droplets appears to be a much better way of handling things. Instead of spraying so many liters through a few seconds of spraying in one swath, probably you may have to go 2 swaths or double spraying. That might be a much better way.

John Spillman:

I think you misunderstood what I said. I wasn't talking about Micronairs. I was talking about spinning disc-type atomizers. I was not advocating large numbers of X-1's. I was simply pointing out that if you tried to use X-1's you would in fact need an excessively large number and certainly 40 X-1's has a big enough drag effect on the aircraft let alone over a hundred. Really, that was leading in to my final comment that we have got to design new atomizers which in fact turn a lot more of the fluid into the spray. With regard to your last point, even if we had a hundred X-1's on an aircraft, I do not believe that the droplets would coalesce to any significant extent. I think that once the droplets are atomized, you can forget collisions as far as changing the spectrum is concerned.

Chairman:

Thank you. This is the end of the technical session. Thank you John, Bernard and David.

SESSION III

SPRAY CLOUD BEHAVIOUR

AIRCRAFT VORTEX EFFECTS ON DROPLET MOTION AND VORTEX STABILITY

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ABSTRACT — The motion of droplets released from the trailing edge of an aircraft wing is initially dominated by the trailing vortex system shed by the aircraft. The formation and structure of the vortex system is described. Trajectories of droplets descending in the velocity field of an ideal vortex system are presented as functions of aircraft parameters (weight, speed, wing span, height etc.), spanwise droplet initial position and droplet diameter. The drop spectrum is characteristic of a forestry insecticide spray. Propeller effects are ignored and the discussion is limited to a "short" time after droplet release before the "long term" transport of the spray by the turbulent atmosphere occurs. Vortex descent is discussed and measured results of vortex instability by core bursting are presented. Data on the time to extinction are shown. Observations on vortex rebound are given based on aerial photography of the vortex system shed by a Harvard aircraft.

RÉSUMÉ — Initialement, les mouvements des gouttelettes relâchées à partir du bord de fuite d'une aile d'avion sont déterminés par l'action du système de vortex induit par le passage de l'avion. Nous présentons des trajectoires de gouttes chutant à travers le champ de vitesse induit par un système de vortex idéal. Les effets sur la trajectoire des paramètres importants de l'avion (poids, vitesse, envergure, altitude etc.), de la position latérale de départ et du diamètre des gouttes sont illustrés. L'action de l'hélice sur les trajectoires a été négligé. Les trajectoires présentées se limitent à de courts temps de vol des gouttes pour lesquels le rôle de la turbulence atmosphérique sur le transport est négligeable. Le mouvement descendant d'une paire de vortex idéale est analysé et nous présentons des données expérimentales sur l'instabilité des vortex par éclatement du noyau et sur le temps de survie des vortex. Nous abordons aussi la question du rebond des vortex en nous appuyant sur des photographies du système de vortex induit par un avion de type Harvard.

ACKNOWLEDGEMENTS

Mr. David Mowbray of the Canadian Broadcasting Corporation supervised the motion picture photography of the Harvard aircraft that was shown at the Symposium. The excellent camera work was performed by Mr. Jacques Gilbert. Mr. Mike Renton of the Flight Research Laboratory made the video pictures of the computer solutions for the droplet trajectories. The video eventually evolved into an edited 16 millimeter motion picture.

LIST OF SYMBOLS

A	droplet frontal area
AR	wing aspect ratio
b	wing span
C	$1/(H_o{}^2) + 1/(E_o{}^2)$
C_L	aircraft lift coefficient = $L/(0.5\ V^2\ S\ \rho)$
C_D	droplet drag coefficient = $D/(0.5\ \rho\ A\ (U-U_{air})^2)$
D	droplet drag
Delta x	downwind vortex translation (Fig. 6 and 7)
E	distance from vortex to plane of symmetry
e	distance aft of wing trailing edge
g	acceleration due to gravity
H	height of the vortex above the ground
K, k_1	constants
L	aircraft lift
m	droplet mass
R_e	Reynolds Number = $ABS[U-U_{air}]\ \delta/\upsilon$
S	wing area
s	theoretical vortex spacing
s′	theoretical vortex semi-spacing
t	time
U	droplet velocity with respect to the ground
U_{air}	air velocity with respect to the ground
V	aircraft speed
v	velocity induced by a vortex
v_d, v_t	descent and translational vortex velocities
x, y	droplet co-ordinates
X, Y	droplet co-ordinates in terms of s′
r	radial distance from a vortex center
r_c	vortex core radius
δ	drop diameter
ϵ	turbulent dissipation rate
υ	air kinematic viscosity
Γ	circulation
β	spanwise co-ordinate
ρ	air density

Subscripts

o	initial
f	final
x, y	components in the x, y directions

INTRODUCTION

In this paper we will discuss vortex formation and vortex descent in ground effect in a somewhat idealized sense. Some real physical effects will be ignored for the initial phases of vortex behaviour. In particular, effects of atmospheric stability require a fairly long time to become important and will not be addressed. Also, the effects of vortex core bursting on vortex descent are ignored. The time at which core bursting occurs is unpredictable and will be discussed later in the context of vortex stability. The ideal vortex discussion will be limited to the first 20 seconds after vortex formation. This period is the average elapsed time before vortex core bursting occurred in our flight experiments.

In the discussion that follows, all of the data and aircraft pictures were drawn from a set of experiments in aerial spraying conducted by the Flight Research Laboratory. A Harvard aircraft was modified and fitted with a full-span boom with evenly spaced nozzles. The aircraft flew at 110 knots at a nominal altitude of 50 feet over flat terrain.

Droplet-vortex interaction will be discussed using a simple model of a vortex. The effects of droplet initial position and diameter on the interaction will be described.

Vortex core bursting will be defined and experimental results of time to burst and time to extinction will be presented.

FORMATION AND STRUCTURE OF THE VORTEX SYSTEM

A review article by Widnall (Ref. 1, 1975) describes the formation and structure of trailing vortices in a very clear and concise manner. In that article, 66 references are quoted and Widnall cites another review with over 1000 pertinent references. However, the review does not discuss vortex core bursting except to say that it is not very well understood and it is commonly observed to occur in trailing vortices. The main facets of vortex formation will be discussed and the historically relevant contributors to the theory will be noted.

The Kutta-Joukowski Theorem (Ref. 2, p. 91) states that an aerofoil at rest in a uniform stream of air at speed V with circulation Γ around it, experiences a lift force of ρ V Γ per unit span. The spanwise lift distribution and the circulation distribution are related by

$$L(\beta) = \rho V \Gamma(\beta)$$

where β is a spanwise co-ordinate and ρ is the air density. The spanwise variation of Γ is shown on Figure 1 (from Rossow, Ref. 3; he uses y for our β) for a high aspect ratio wing. The circulation distribution on the wing is shown with an elliptical spanwise variation which makes the wing very efficient by minimizing the induced drag. The above result was first derived by Kutta in 1902 and independently by Joukowski in 1906. Spreiter and Sacks (Ref. 4, 1951) cite the work of Prandtl in 1918 and 1919 where the assumptions that are customarily used today about the shed vorticity were first made. Prandtl wrote that the vortex wake should be designated as a thin vortex sheet which is flat at the wing trailing edge and extends downstream from the wing. Widnall (Ref. 1) describes how Stokes' Theorem kinematically relates the circulation to the vorticity.

A theory due to Betz (Ref. 5, 1933) uses three conservation equations of circulation to relate the structure of the vortex sheet behind an isolated half-span wing to the structure of a single, fully developed vortex. This topic is currently being intensively studied by numerical methods. Widnall (Ref. 1) describes some of the problems being faced in this branch of research. A current study by Stremel (Ref. 6, 1984) is an example of the modern numerical methods being used to examine trailing vortex systems.

Moving in a direction downstream from the trailing edge, the vortex sheet stretches and the edges of the sheet begin to curl which starts the roll-up process. The two coils (Fig. 1) finally form two fully developed vortices. The distance behind the wing for the full roll-up to occur was derived by Spreiter and Sacks (Ref. 4) from similarity considerations and by Kaden in 1931 (cited in Ref. 4) by a theoretical analysis. The result is

$$e/b = K\ AR/C_L$$

where e is the distance aft of the trailing edge at the position where the roll-up process is complete, b is the wing span, K is a constant, AR is the wing aspect ratio and C_L is the aircraft lift coefficient. Kaden calculated the value of K to be 0.28. The centers of gravity of the vortices asymptotically approach the separation distance

$$s = \pi b/4$$

for elliptically loaded wings. Water tank experiments (Ref. 4) were conducted using a rectangular wing of aspect ratio 5. The measurements showed that the separation distance s was achieved within 5 or 6 chord lengths, about one span. The distance aft of the wing where full roll-up could be achieved at a C_L of 0.5 would be 2.8 spans. For the Harvard aircraft at 110 knots, the vortices would be fully rolled up in about 2/3 of a second (b = 42 feet).

The trailing vortex in its simplest manifestation is an ideal, inviscid, potential vortex with an induced velocity field v(r) given by

$$v(r) = \Gamma/(2\pi r)$$

where r is the radial distance from the vortex center. The value of Γ is obtained from

$$L = \rho V \Gamma s$$

where the variable Γ in this equation is taken to be the strength of the isolated trailing vortices. For steady level flight, the lift L equals the aircraft weight. The span loading L/b determines the vortex strength at speed V. Generally, heavier airplanes have larger span loadings and higher values of Γ. The same aircraft flying slower would have an even larger value of circulation.

However, this form of the vortex admits an infinite velocity at the center. This is physically impossible; therefore, there must be a core. Spreiter and Sacks (Ref. 4) assume that the core is circular in shape and that it rotates as a solid body. They are able to relate the kinetic energy of the vortex flow and the aircraft induced drag. If the span loading is elliptical, the radius of the finite core is

$$r_c = 0.0775\ b$$

The velocity field around the vortex center is now described by

$$v(r) = k_1 r \qquad r < r_c$$

$$v(r) = \Gamma/(2\pi r) \qquad r > r_c$$

where k_1 is chosen to match the value of v from both equations. Figure 2 shows the velocity field. Thus, we have the lowest approximation of a fully rolled-up trailing vortex. However, for detailed flow investigations, Donaldson et al. (Ref. 7, 1974) indicate that a more detailed description of the vortex core is desirable. In addition, the value of Γ is sometimes taken to decrease with time due to viscous effects. In this work, the time variation of the circulation is neglected considering that long term solutions are not being sought.

The two vortices from each wing tip rotate with opposite sense making the center line of the aircraft into a plane of symmetry. The ground is constructed by adding image vortices with opposite sense to the primary vortices above them (Fig. 3). The addition of the image vortices forces satisfaction of the condition of no flow through the ground plane. The vortices and their images each move under the vector sum of the velocities induced by the other three vortices. The induced velocity from any vortex on any other will be perpendicular to the line joining their centres and will have a sense following the right-hand rule. Dee and Nicholas (Ref. 8, 1969) give all the algebraic steps to show that the trajectory of the descending vortex in the first quadrant (Fig. 3) is given by

$$1/H^2 + 1/E^2 = C$$

where C is evaluated from the initial values of H and E. The trajectories of the others are obtained by suitably changing the signs of H and/or E. This result is true only when the point at which an induced velocity is calculated is more than a few core diameters away from the inducing vortex (Ref. 8). Also, the result is restricted to a neutrally stable atmosphere, no wind shear and a constant wind velocity. Axial flow effects are ignored. The asymptotic height H_f of the vortex above the ground (when the horizontal translation is large) is given by

$$H_f/s' = H_0/s'(1 + (H_0/s')^2)^{-0.5}$$

where s' is the semi-spacing of the vortices. When the initial height is large, the asymptotic height of the vortex is s'.

The initial velocity of the vortex descent out of ground effect is

$$v_d = -\Gamma/(2\pi s)$$

The term "out of ground effect" means that the induced velocities from the image vortices are negligible while "in ground effect" means that the induced velocities are important. In general, Dee and Nicholas (Ref. 8) show that, in ground effect, the descent velocity is

$$v_d = -\Gamma H^2/(4\pi E(E^2 + H^2))$$

They also provide a relationship between E and H. This relation is used to eliminate E so that v_d is a function of H only. The result is:

$$v_d = -\Gamma(CH^2 - 1)^{1.5}/(4\pi C H^3)$$

Similarly, the translational velocity parallel to the ground is given by

$$v_t = \Gamma(CE^2 - 1)^{1.5}/(4\pi C E^3)$$

Both v_d and v_t are proportional to Γ but the path of the vortex depends only on H_0 and E_0. The latter is prescribed once the aircraft span is known. As the primary vortex pair moves closer to the ground, the descent velocity decreases and the translational velocity increases.

We will use this idealized model of the trailing vortex wake of an aircraft as two fully rolled-up vortices with finite cores, each moving under the induced velocities of the other primary vortex and the two image vortices. The validity of this model is restricted to "short" times because the effects of turbulence, wind shear, atmospheric stability and vortex stability alter the geometry of the problem, the forces on the vortex system and the very existence of the vortex core. However, time is required for the effects of these variables to become important.

FLIGHT EXPERIMENTS

The wing tip vortices in the flight experiments were marked by smoke (Fig. 4). Aerial and ground cameras photographed the positions of the vortex cores so that measurements of the vortex trajectories could be made. Figure 5 shows that the vortices have descended some distance after the aircraft passage. An asymmetric sinuous motion of the vortices can be observed.

Figure 6 shows the measured trajectory of a vortex pair descending from an initial height of about 50 feet. The 's' and 'p' refer to the starboard and port vortices respectively. The aircraft is taken to be flying perpendicular to the paper with the cross wind (small) blowing from left to right in the positive Delta x direction. The port vortex is the downwind vortex in this case. The numbers at the end of each trajectory are the times in seconds when the measurements on that vortex ceased. This cessation of analysis sometimes occurred during processing of the many films of flight data because the films became unreadable but usually the analysis stopped because one vortex became unstable before the other. The analysis of all the vortex trajectories measured during the set of flight experiments is reported by Drummond et al (Ref. 9, 1987). The vortices (Figure 6) are seen to descend uniformly. The analysis ceased before the vortices reached the theoretical height of s' above the ground. It was observed from the analysis of the above mentioned flight experiments that only one of the nine trajectories with an initial height greater than 38 feet descended below the theoretical asymptote. The average final height was 26 feet and the theoretical symptote would be 16½ feet for the Harvard.

Figure 7 shows another experimentally derived vortex trajectory. In this case, the initial height is about 35 feet. The downwind vortex descends and then rises to a point above its initial height. This effect is known as vortex rebound or bounce. The classical theory discussed above cannot explain this phenomenon.

A wind tunnel study by Harvey and Perry (Ref. 10, 1971) lead to an explanation of why the downwind vortex should rise. They concluded that the vortex induces a cross flow on the ground and that the boundary layer resulting from the cross flow has to negotiate an adverse pressure gradient after passing under the vortex. When the vortex is sufficiently near the ground the pressure gradient can be strong enough for the boundary layer to separate. A bubble forms containing vorticity of the opposite sense to the primary vortex. A secondary vortex results and it remains outboard of the main core. The secondary vortex will induce an upward velocity on the primary vortex causing it to rise. The experimental data of Harvey and Perry (Ref. 10) were taken with the wing at ½ and at 1 chord length above the tunnel floor, which is very close to the solid boundary. For the Harvard aircraft, flight at a height of ½ a chord is impossible because the propeller would contact the ground. Even at one chord length, with the undercarriage down to protect the propeller, the wheels would be nearly touching the ground.

The conclusions of a theoretical study by Walker (Ref. 11, 1978) of the boundary layer under a rectilinear vortex agreed with the measurements of Harvey and Perry (Ref. 10). Walker notes that the inviscid, ideal vortex descent model violates the no-slip condition on the ground and thus the model becomes inappropriate near the ground. Walker presents a number of arguments to suggest that an explosive eruption of the boundary layer is to be expected after a "long" time.

In the set of experiments using the Harvard aircraft, only the downwind vortex was observed to rebound and a rebound occurred only when the aircraft height was below 38 feet. For aircraft heights between 38 and 65 feet, the vortices descended in a manner similar to the trajectory shown in Figure 6. The effect of initial height on the occurrence of vortex rebound has not been noted previously (to the author's knowledge) and the above conclusion seems to contradict the theory of Walker and, more importantly, the measurements of Harvey and Perry. However, if the boundary layer under the vortex does not separate, then there will be no secondary vortex to induce upward motion on the downwind vortex. None of the Harvard flights took place as close to the ground as in the experiments of Harvey and Perry. In fact, the 38-foot boundary is 6.2 chords above the ground for the Harvard. Perhaps the adverse pressure gradient was not strong enough to force separation and perhaps the vortex strength was reduced because of the longer time required to come into close proximity to the ground.

Using the ideal model, the asymptotic height above the ground for a vortex equals its initial height when the initial height is small. Otherwise, it equals s′ when the initial height is large. Thus, the strength of the adverse pressure gradient is expected to be much lower for a higher initial vortex height. The lower the adverse pressure gradient, the less chance there is for the boundary layer to separate. Even if it did separate, the induced velocity would be lower because of the relatively larger distance between the primary and secondary vortices.

DROPLET-VORTEX INTERACTION

Droplet-vortex interaction will be discussed by use of the equations of motion of the droplet, the ideal vortex velocity field (Fig. 2) and the induced velocities of the primary vortices and their images (Fig. 3). This idealized approach will be a first approximation to the real situation. Hopefully, the session on spray modelling will cover the droplet-vortex-atmosphere interaction more completely with results that apply for a longer period of time.

A short time after leaving the nozzle, the initial velocity of the droplet is nullified by drag and the droplet is moving at its terminal velocity with respect to the air. The air has its own velocity field (from the vortices) that moves with respect to the ground. Thus, the droplet's trajectory is determined by its terminal velocity and the velocity of the air. The terminal velocity is determined by the drag-to-mass ratio of the drop. The degree to which the air velocity field affects the drop trajectory depends on the magnitude of the drag-to-mass ratio of the drop. Large drops have a low value while small drops have a large value. One would expect small drops to follow the local flow quite closely while large drops would move independently of the velocity field of the air.

The droplet size and emission point determine the extent of droplet-vortex interaction. After the vortex system becomes unstable, leading to its extinction, the turbulent atmosphere carries any affected droplets.

The equations of motion of the drop in earth-fixed axes are:

$$m\,dU_x/dt = -D_x$$

$$m\,dU_y/dt = -D_y - mg$$

where

$$D = C_D(R_\infty)0.5\,\rho\,A\,(U-U_{air})\left\{ABS[U-U_{air}]\right\}$$

U and U_{air} are the velocities of the drop and the air with respect to the fixed axes. The drag coefficient C_D is a function of the Reynolds Number R_∞. The droplet's frontal area is A. The drag coefficient of a sphere as a function of Reynolds Number can be found, for example, in Reed (Ref. 12, 1954). Also, Reed provides a discussion on droplet-vortex interaction but his results apply to much larger drops that were fashionable in 1954.

The two equations of motion are integrated numerically as an initial value problem. The vortex wake is assumed to be fully rolled up and propeller effects are ignored. The drop's initial velocity is taken to be equal to U_{air} at the point of emission on the wing trailing edge. Droplet evaporation is not considered.

The equations of motion were integrated for drop diameters from 200 to 50 microns. The droplets were placed at 12 spanwise positions representative of nozzle placements on the Harvard aircraft. The first nozzle was placed 6-1/3 feet from the aircraft center line and the remaining nozzles were placed every 1-1/3 feet out to the wing tip. The spray spectrum from an operational spray aircraft has a volume mean diameter between 90 and 100 microns and a maximum drop size less than 250 microns. Thus, each nozzle will eject a weighted sum of drops in the size range being discussed here, most of the drops being under 100 microns.

Before discussing solutions to the equations of motion, two photographs of the Harvard are presented to illustrate droplet-vortex interaction. In Figure 8, the Harvard is shown flying overhead (Ref. 13). The paths of the drops from each nozzle are clearly visible as are the two vortex cores (dark) in the center of the spray cloud. The path from each nozzle is seen to wrap around the vortex core with more curvature from the nozzles nearer the wing tip. In the center, the spray is less affected by the vortex. An outer boundary of the spray cloud around each vortex is clearly visible.

Figure 9 shows a rear view of the aircraft during the same run after it has passed overhead. The spray from the center area of the boom appears to be much less affected by the vortices as expected. Sinuous motion in the vortex system is apparent quite soon after vortex formation.

> NOTE — in the oral presentation, a motion picture of the evolution of the computer solutions was shown. Here, the final evolved form of each solution is presented.

Figures 10 to 20 show computer solutions for droplet trajectories. All figures show the wing at a height of 1.4s′ (23 feet for the Harvard) as well as the starboard vortex trajectory. The view is from the rear of the aircraft. The distances X and Y are measured in terms of s′. A circle at the end of a trajectory means that the drop had hit the ground before 20 seconds had elapsed. The square means that the drop had passed the 4s′ boundary before the 20-second limit. Each symbol is 1/10 of a second apart. Thus, closely spaced symbols indicate a low droplet velocity. Some figures show many trajectories from various initial positions while others do not. In the latter case, the figures would have become too cluttered to reveal anything about the droplet trajectories if more lines had been included.

Examination of the figures shows that large drops near the aircraft center fall out but, as the emission point nears the vortex, all the droplet trajectories are markedly affected by the vortex. Small drops are dominated by the vortex no matter where they start on the wing. These results were shown clearly in Figure 8 and 9 from real flight observations.

Figure 21 shows the trajectories of three 50-micron drops emitted at the same spanwise location but at three heights. The vortex trajectories are also shown. Each one of these is different because the initial height is different. The degree of droplet-vortex interaction is about the same; the maximum distance from the drop to the vortex track appears to be about equal for the three trajectories. However, the lateral dispersion of the droplets is larger nearer the ground because the lateral velocity of the vortex is larger.

Figure 22 shows the tracks of two 150-micron drops for two values of the vortex strength. Here, the trajectory marked Γ_2 applies to a vortex with twice the strength of the vortex marked Γ_1. The vortex tracks are the same for both vortex strengths but the track appropriate to Γ_2 (dotted) is extended because its velocity is twice that of the Γ_1 vortex. The droplet-vortex interaction is about the same except that the lateral dispersion caused by the higher strength vortex is larger. The vortex moves farther in the 20-second period of interest. Increasing the aircraft weight or decreasing its velocity serve to increase circulation.

VORTEX STABILITY

Vortex instability by core bursting has been alluded to in previous paragraphs. Review papers by Hall (Ref. 14, 1985) and by Leibovich (Ref. 15, 1984) provide good background for the discussion on vortex core bursting. Figure 23 shows the same vortex pair that was studied in Figure 5 but at a later time. One vortex is still intact but the other has suffered a vortex core breakdown commencing at the left side of the picture. The mechanism of core bursting is still an unsolved aerodynamic problem. According to Faler and Leibovich (Ref. 16, 1977), there are six different types of vortex breakdown. Tombach et al (Ref. 17, 1977) state that not even the definition of core bursting is agreed upon. Escudier (Ref. 18, 1986) concludes that there is no general agreement on the facets of the flow which are essential to core bursting.

The description of core bursting used in this work is based on the analysis of motion pictures of the Harvard aircraft with its trailing vortices marked by smoke. A description of core bursting follows. Suddenly, the vortex core starts to thicken and a stagnation point is apparently formed. An axial flow commences from that point in an upstream direction towards the aircraft. Sometimes, in addition, there is a downwind axial flow of lower intensity. There is usually a complete break in the smoke because the axial flow has pushed the smoke particles away. However, the core is not always totally destroyed. Sometimes a vestigial filament of smoke remains in the center. Tombach et al (Ref. 17) show experimental data which indicate that there is still rotational flow in the vortex even after core bursting. Approximately ¼ of the vortex intensity was preserved in the two cases they reported.

Figures 24 and 25 show the measured times to burst versus the turbulent dissipation rate ϵ to the 1/3 power for the port and starboard vortices respectively. The time to burst is defined as the first instant after aircraft passage that a break in the smoke trail could be identified. The higher the turbulence, the larger the value of ϵ. As ϵ increases, the time to burst decreases. Turbulence is the apparent trigger for vortex core bursting. Tombach et al (Ref. 17) developed a model for predicting the time to burst and ϵ to the 1/3 power emerged as the independent variable.

The data are plotted versus the turbulent dissipation rate because Lissaman et al (Ref. 19, 1973) state quite emphatically that the only quantity to which any property of a turbulent flow in the inertial subrange can be related is the turbulent dissipation rate. This quantity was measured using mainly a commercial sonic anemometer but measurements were also made using the Flight Research Laboratory sonic anemometer. The latter device is described by Barszczewski (Ref. 20, 1988) and the results of the assessment of both anemometers in a wind tunnel are given by Drummond and Barszczewski (Ref. 21, 1985). The calculation of the turbulent dissipation rate is discussed by Drummond et al (Ref. 9).

For both Figures 24 and 25, the open symbols refer to data taken in 1985 and the solid symbols refer to measurements taken in 1986. The arrow on a symbol indicates that core bursting had not occurred when the film became unreadable. The dotted lines are experimental correlations made by Tombach (Ref. 22, 1973). The term "corrected for height" on the figures means that the value of the turbulent dissipation rate as measured by the anemometers on the meteorological tower was corrected to be the value that would have been obtained at the height of aircraft passage. Lissaman et al (Ref. 19) show that ϵ is inversely proportional to height. The experiments reported by Drummond et al (Ref. 9) confirm the above statement on average.

The Tombach data (Ref. 22) were taken using a Cessna 170 light aircraft out of ground effect at an altitude of about 400 feet. He found both sinuous (Crow (Ref. 23, 1970)) and core bursting forms of vortex instability, the latter form predominating. The vortices observed in the Harvard flight experiments never became unstable by sinuous instability.

The upper boundary of Tombach on Figure 24 (port vortex) contained all the Harvard data quite well, while the lower boundary embraced only the 1986 data in a satisfactory manner. Apparently, some of the port vortices during the tests in 1985 burst prematurely. Data in Drummond et al (Ref. 9) show that the port vortex burst before the starboard vortex in every case during the 1985 experiments.

A tentative explanation for the early bursting of the port vortex is that a small triangular antenna that was mounted on the underside of the wing near the wing tip shed a locally strong vortex (conical flow). This vortex then wrapped itself around the primary vortex and triggered core bursting. The antenna was removed for the 1986 tests and the data for that year were well bounded by the Tombach correlations. The starboard vortex (Fig. 25) time to burst data were always well contained within the Tombach boundaries in each year of testing. The starboard wing tip had no external devices mounted nearby. Perhaps early vortex instability could be initiated by placing a vortex generator near an aircraft wing tip.

Figure 26 shows the time to axial flow (burst) versus the time to extinction. Arrows on some symbols indicate that either bursting and/or extinction could not be determined from the films. The time to extinction is not a precise measurement and some judgement was used. Extinction was said to have occurred when there was no organized vortex core near the spray sample line in a global sense. The time to axial flow measures the start of instability that leads to extinction and is a measure of a local event.

The data show that between 5 and 18 seconds elapsed from the onset of instability until extinction. No correlations on port/starboard or 1985/1986 data are evident. Once bursting commenced, no effect of the antenna could be seen. No matter what the turbulence level, the time required to destroy the vortex is still between 5 and 18 seconds.

> **NOTE** — In the oral presentation, a motion picture of two passes by the Harvard aircraft while spraying (Mowbray (Ref. 13)) with its vortex cores marked by smoke was shown that illustrated the main points of the presentation. No conclusions were made.

CONCLUSIONS

Vortex formation and descent have been discussed in an idealized sense. Vortex rebound occurred whenever the aircraft height was less than 38 feet and an attempt was made to resolve apparent contradictions between the flight test data reported here and published wind tunnel tests.

Droplet-vortex interaction was computed using the classical descent model and the simplest model of the rolled-up vortex that removed the singularity at the vortex center.

Experimental data on vortex core bursting have been presented. A method to initiate early vortex instability was suggested. The time to extinction of a vortex was shown to be independent of the turbulence after bursting had commenced. Bursting was accelerated by higher air turbulence.

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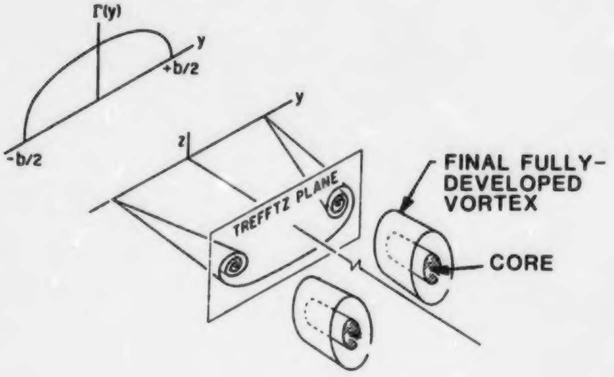
Γ(y)
y
+b/2
-b/2
y
z
TREFFTZ PLANE
FINAL FULLY-DEVELOPED VORTEX
CORE

FIG. 1: VORTEX SYSTEM ROLLING UP

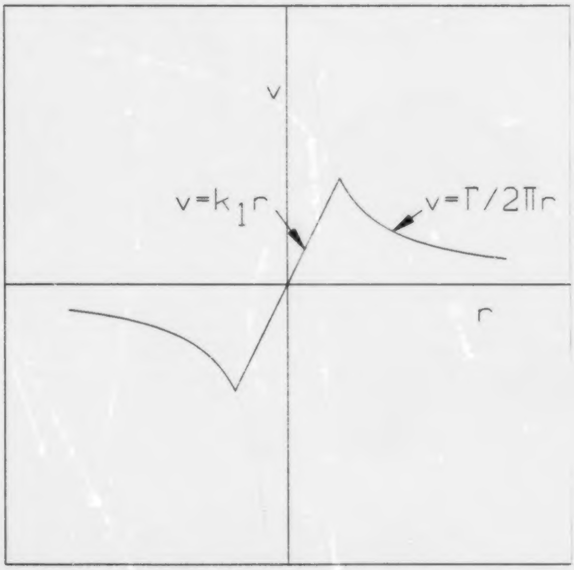

FIG. 2: VELOCITY FIELD FROM A ROLLED UP VORTEX

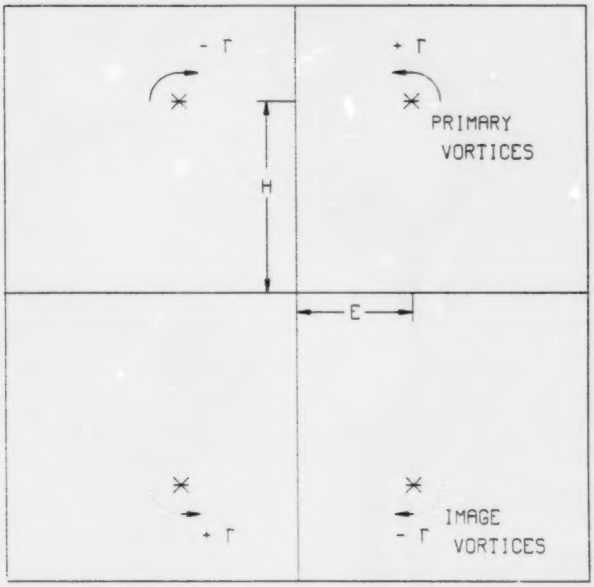
- Γ
+ Γ
PRIMARY VORTICES
H
E
+ Γ
- Γ
IMAGE VORTICES

FIG. 3: VORTEX SYSTEM IN GROUND EFFECT

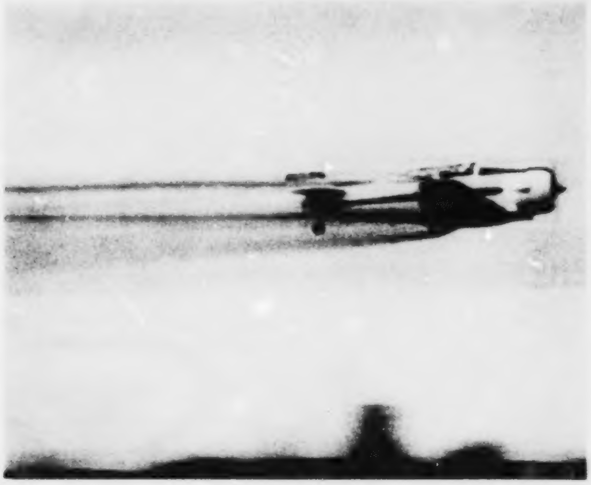

FIG. 4: HARVARD AIRCRAFT SHOWING SPRAY AND VORTEX CORES MARKED BY SMOKE

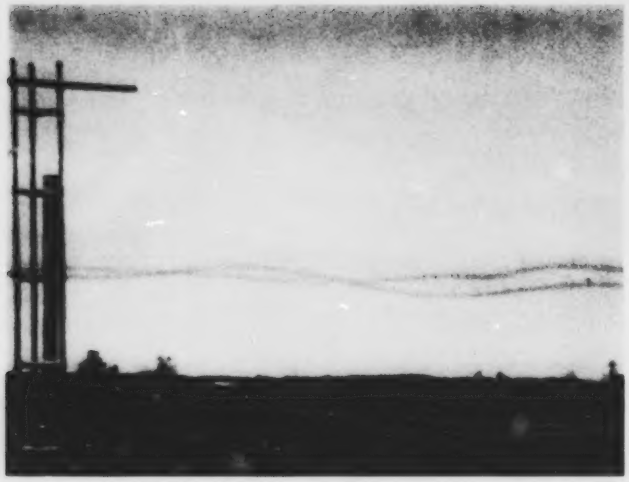

FIG. 5: THE DESCENT OF A VORTEX PAIR

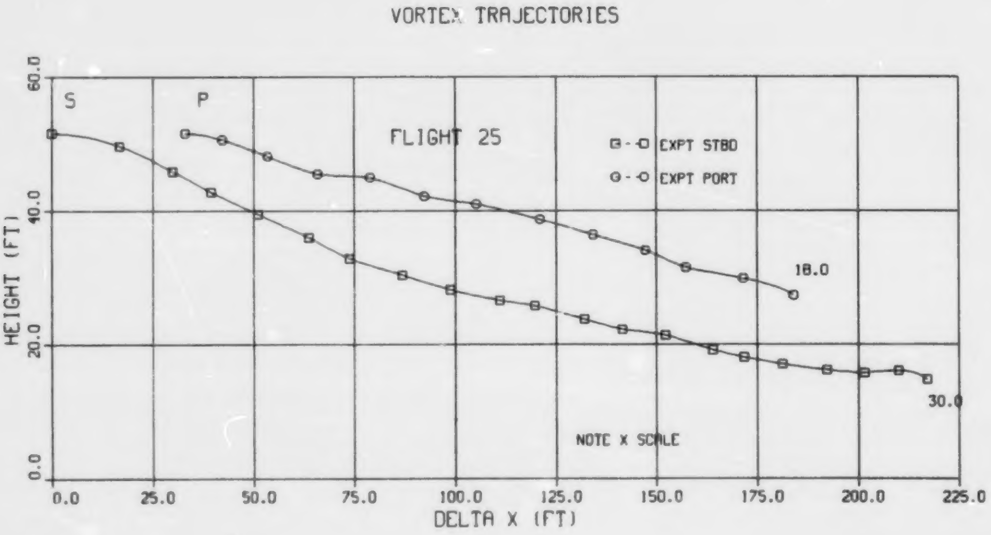

FIG. 6: MEASURED VORTEX TRAJECTORY FROM 50 FEET

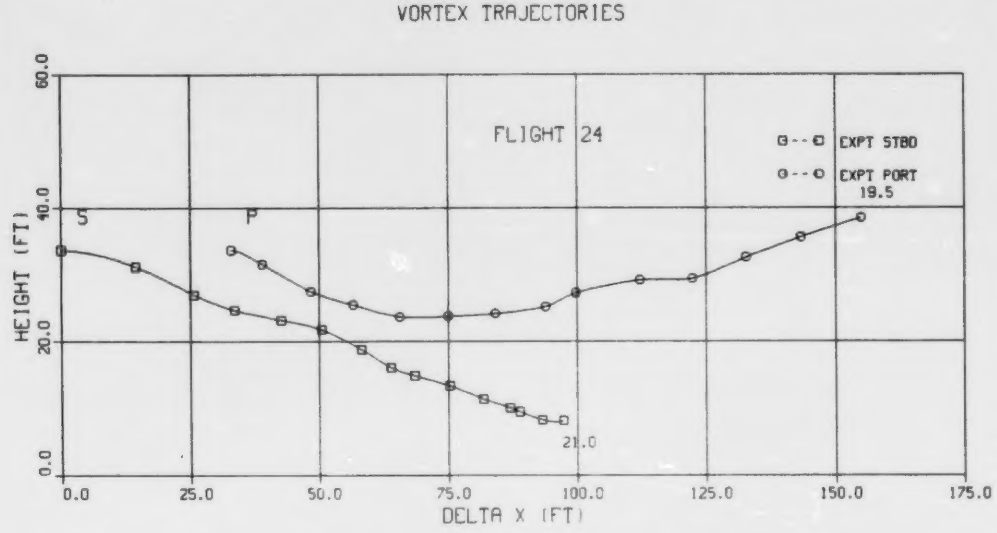

FIG. 7: MEASURED VORTEX TRAJECTORY FROM 35 FEET

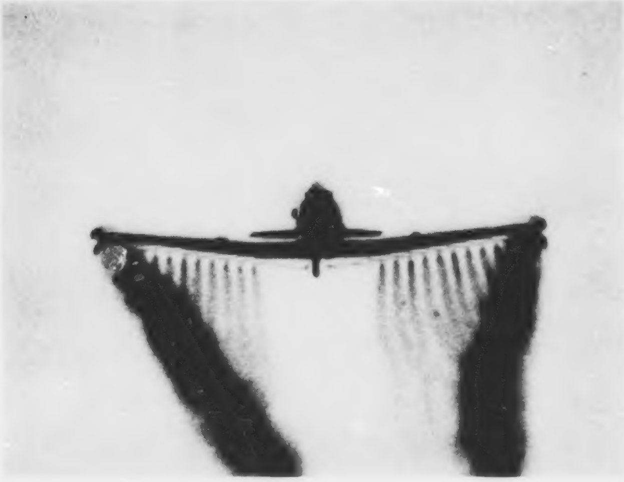

FIG. 8: DROPLET-VORTEX INTERACTION – HARVARD OVERHEAD

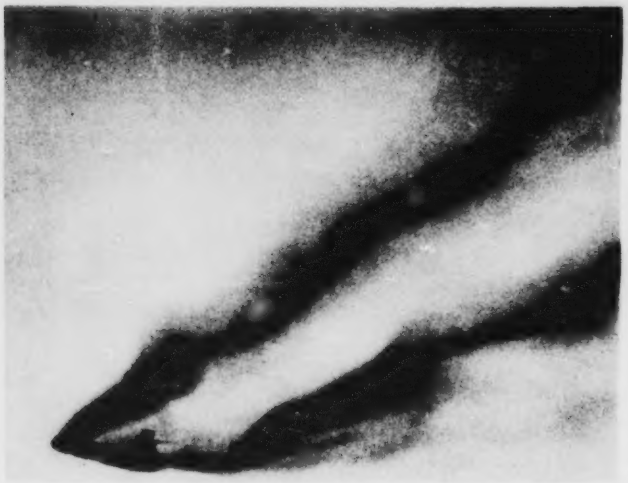

FIG. 9: DROPLET-VORTEX INTERACTION – REAR VIEW OF THE HARVARD

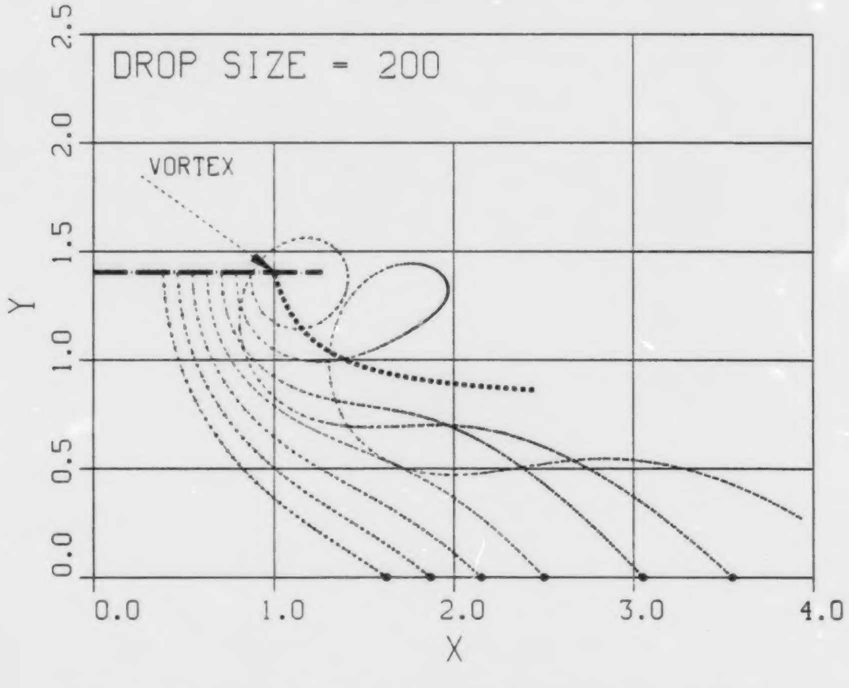

FIG. 10: TRAJECTORIES OF 200μ DROPS FROM 7 INBOARD NOZZLES

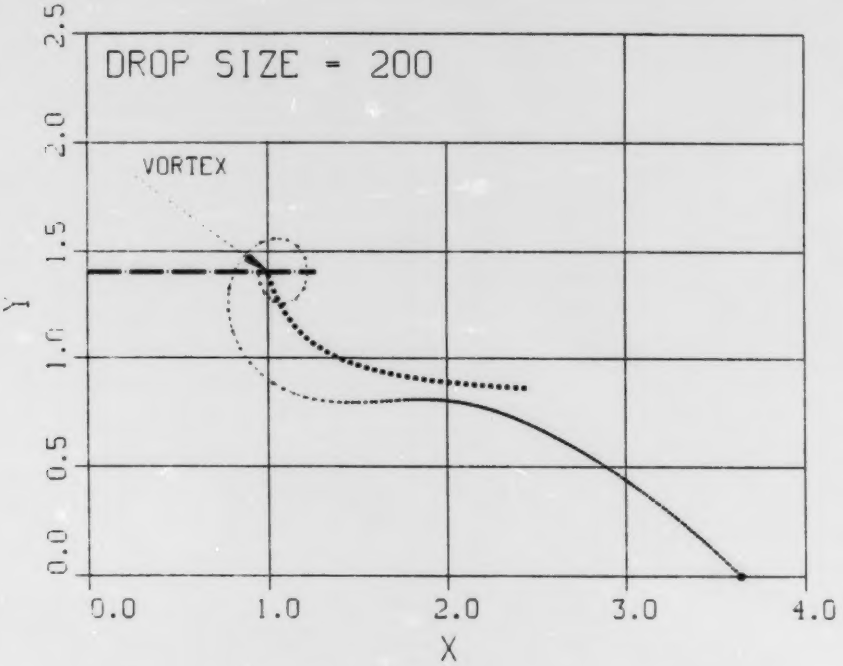

FIG. 11: TRAJECTORY OF A 200μ DROP NEAR THE VORTEX

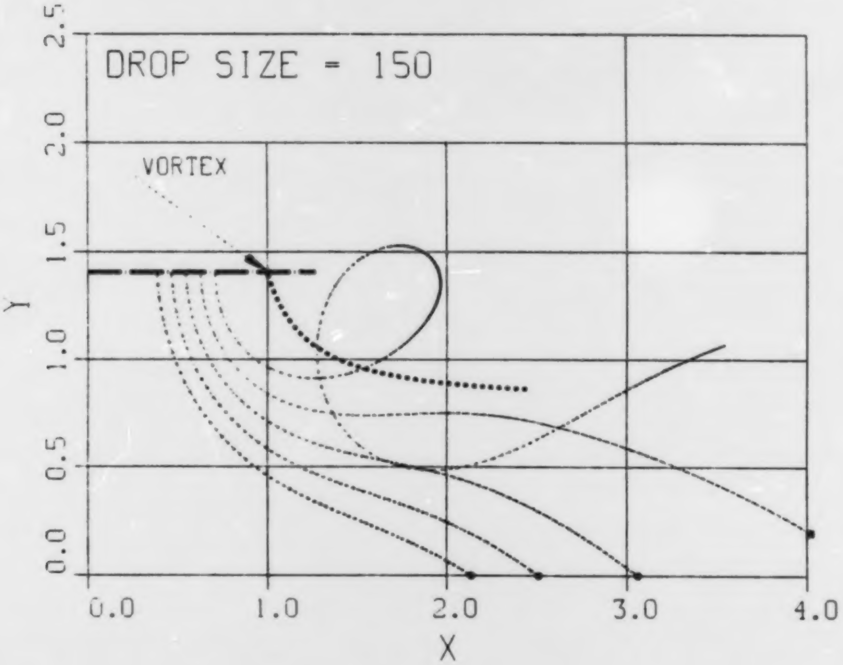

FIG. 12: TRAJECTORIES OF 150μ DROPS FROM 5 INBOARD NOZZLES

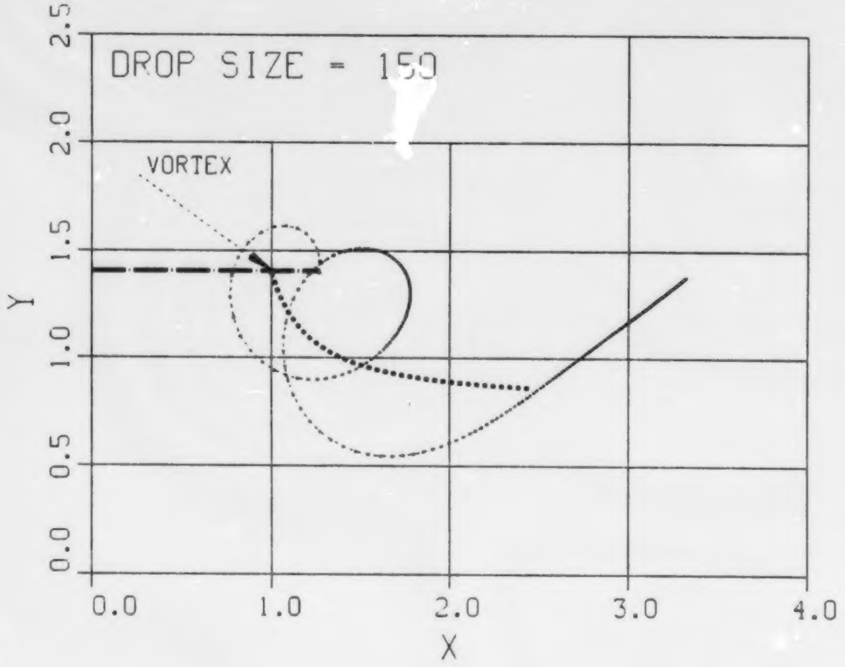

FIG. 13: TRAJECTORY OF A 150μ DROP AT THE WING TIP

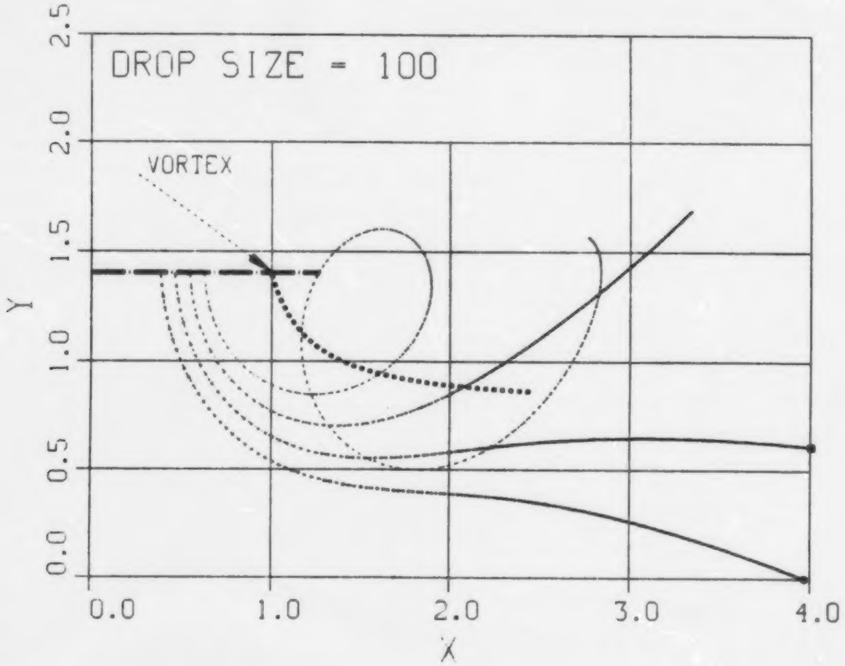

FIG. 14: TRAJECTORIES OF 100μ DROPS FROM 4 INBOARD NOZZLES

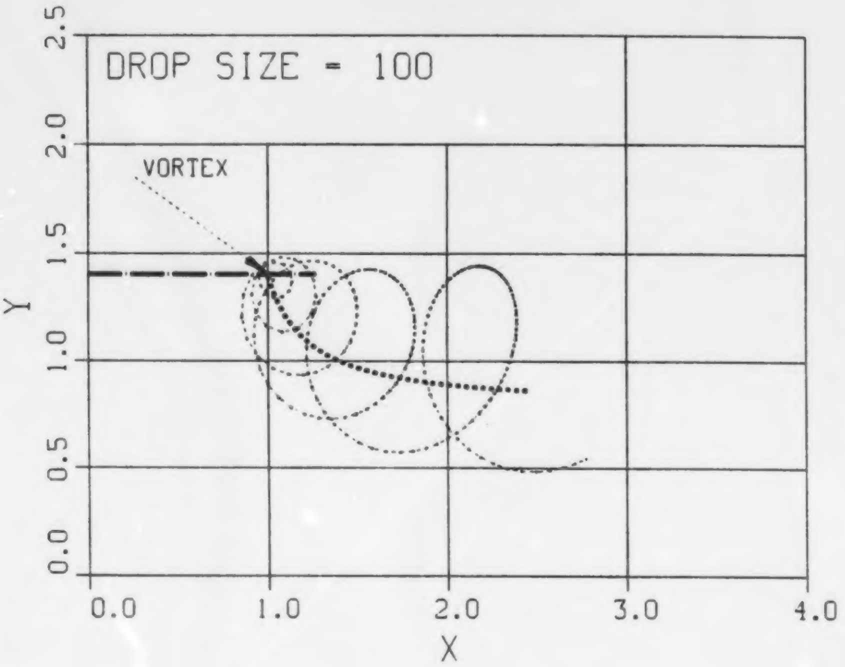

FIG. 15: TRAJECTORY OF A 100μ DROP NEAR THE VORTEX

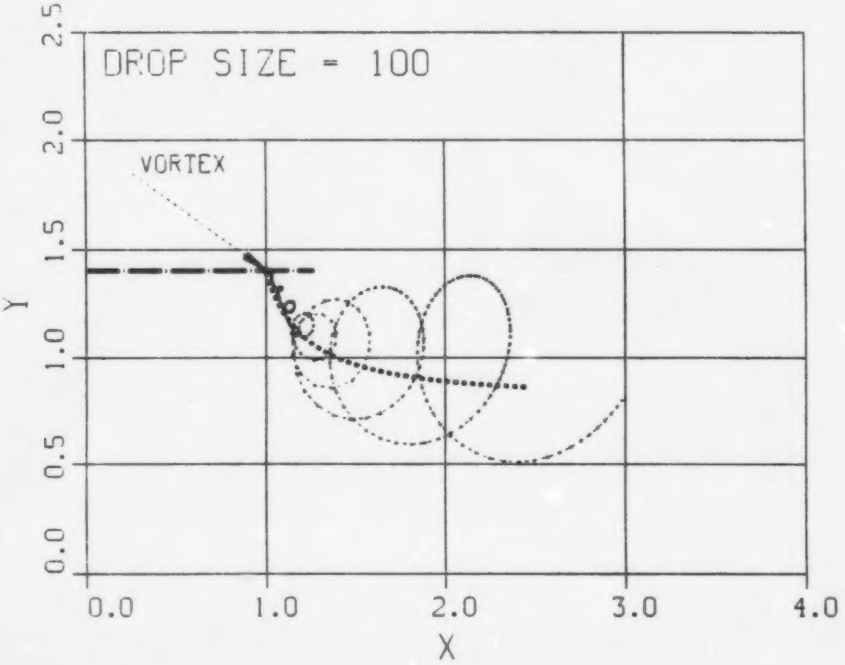

FIG. 16: TRAJECTORY OF A 100μ DROP AT THE VORTEX

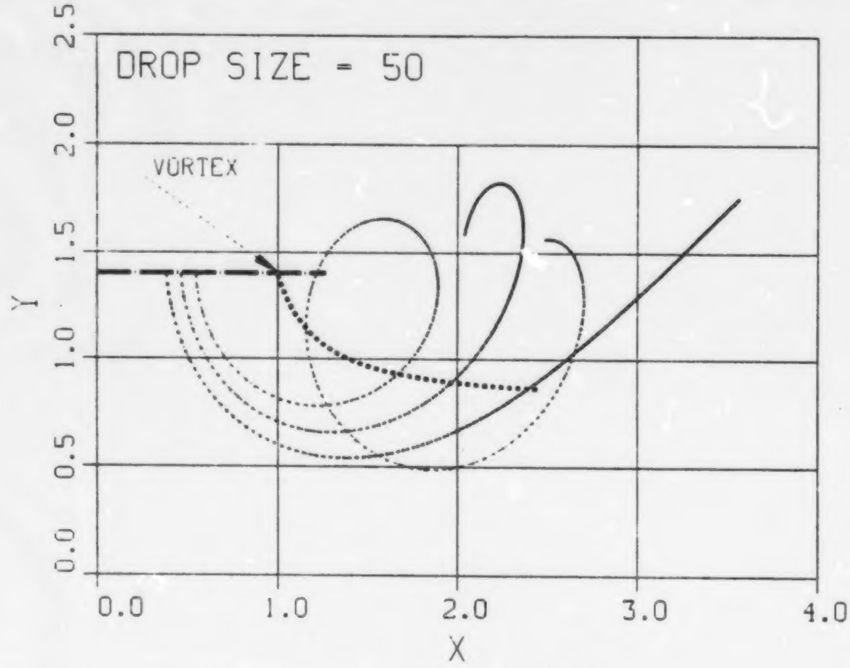

FIG. 17: TRAJECTORIES OF 50μ DROPS FROM 3 INBOARD NOZZLES

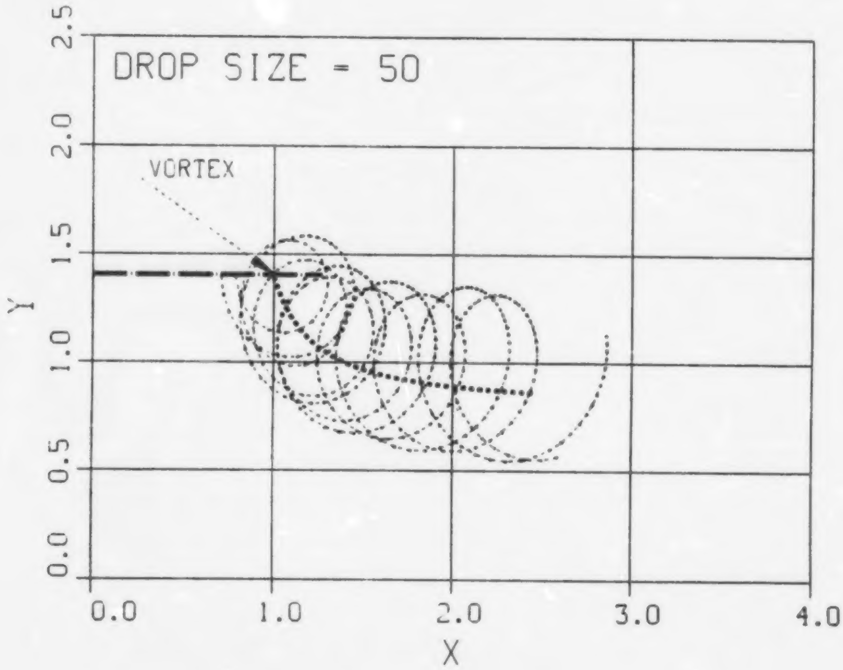

FIG. 18: TRAJECTORIES OF 50μ DROPS FROM 2 INBOARD NOZZLES

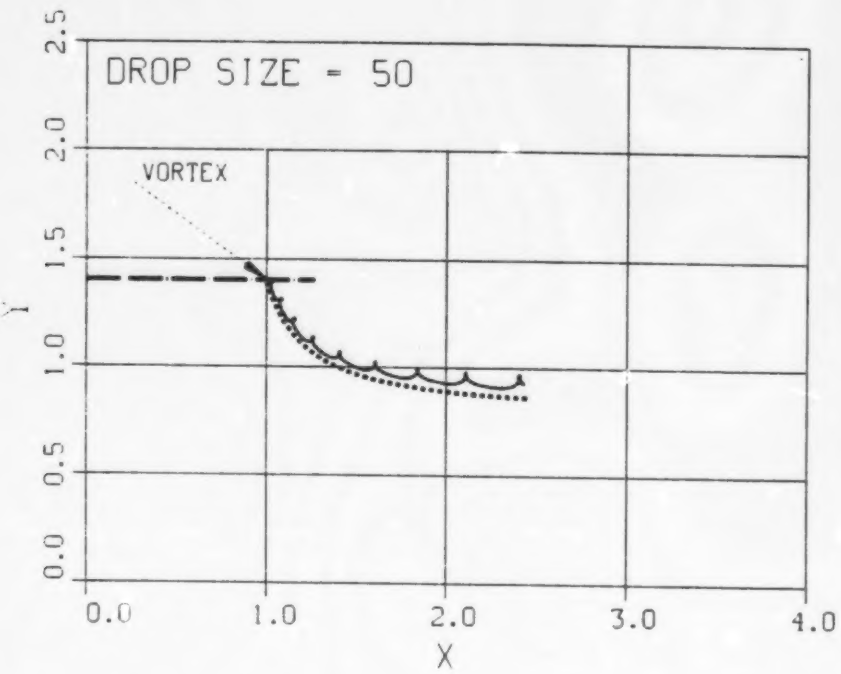

FIG. 19: TRAJECTORY OF A 50μ DROP AT THE VORTEX

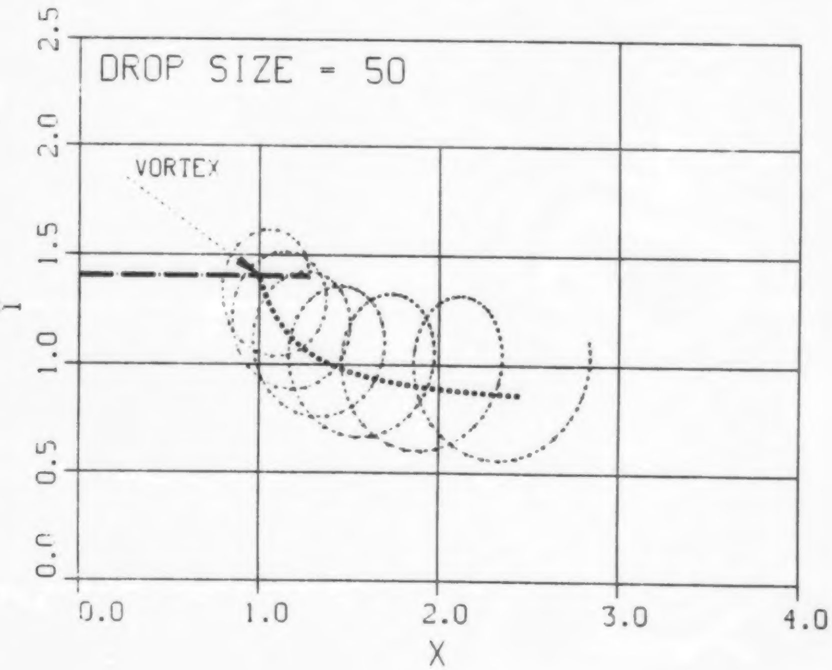

FIG. 20: TRAJECTORY OF A 50μ DROP AT THE WING TIP

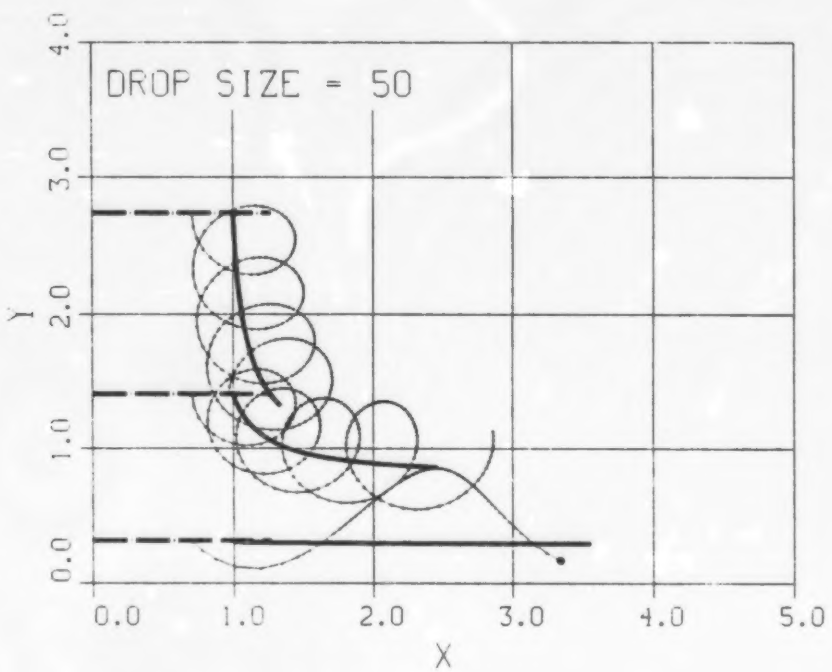

FIG. 21: TRAJECTORIES OF THREE 50 MICRON DROPS FROM THREE ALTITUDES

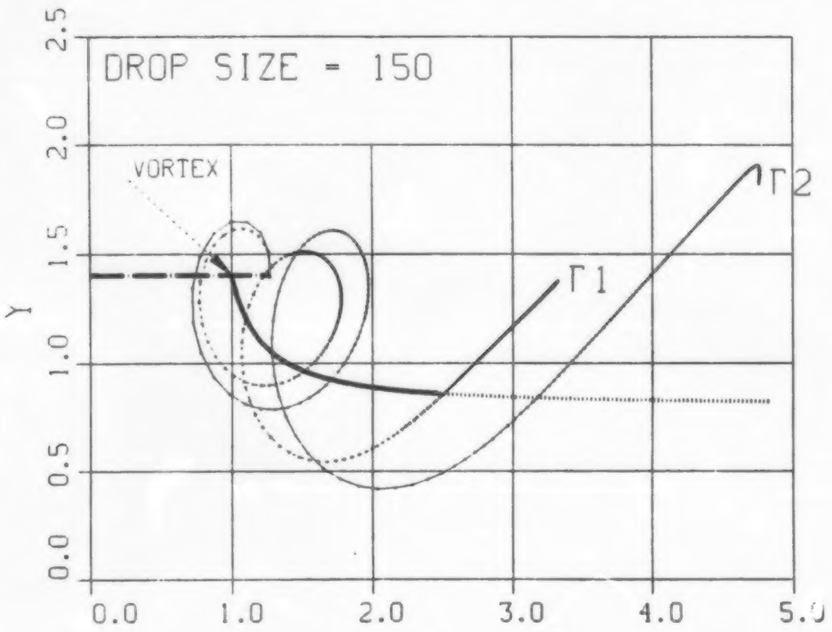

FIG. 22: TRAJECTORIES OF TWO 150 MICRON DROPS FOR TWO VALUES OF CIRCULATION

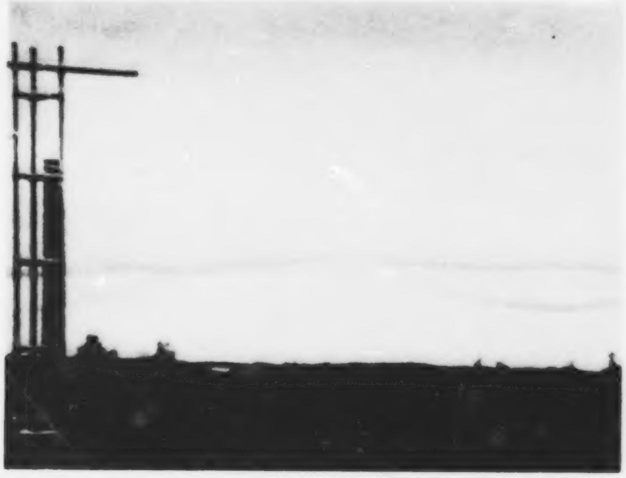

FIG. 23: CORE BURSTING OF A VORTEX

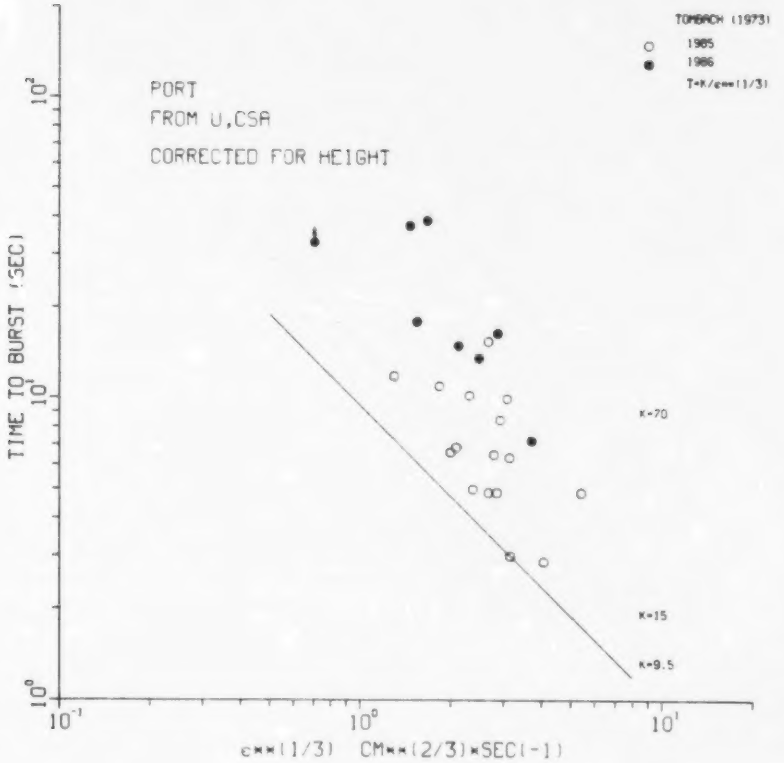

FIG. 24: TIME TO BURST FOR THE PORT VORTEX

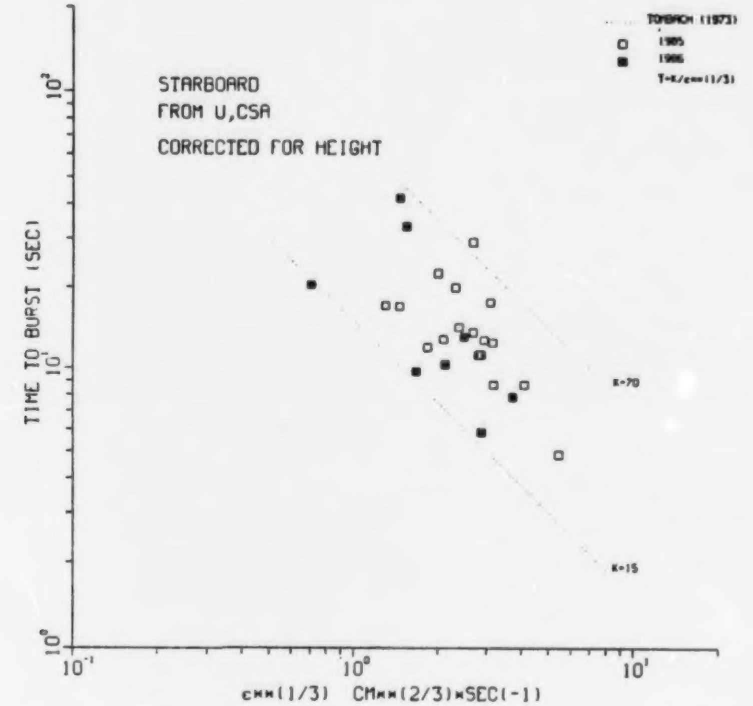

FIG. 25: TIME TO BURST FOR THE STARBOARD VORTEX

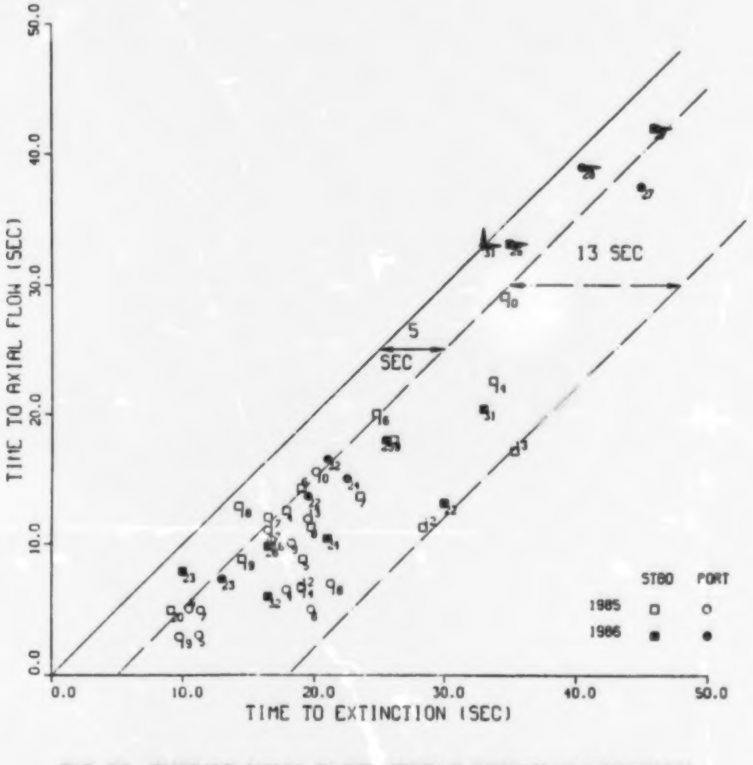

FIG. 26: TIME TO AXIAL FLOW VERSUS TIME TO EXTINCTION

FACTORS AFFECTING THE MOVEMENT OF SPRAY DROPLETS ABOVE A FOREST CANOPY

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ABSTRACT — The dispersion of spray droplets above a forest canopy is influenced not only by droplet size, but by meteorological factors such as wind speed and atmospheric turbulence. Atmospheric turbulence is in turn influenced by the aerodynamic characteristics of the canopy, local topography and the prevailing temperature profile. The influence of these factors and their importance in practical operations is discussed. The importance of a knowledge of evaporation rates is stressed and the accuracy of current mathematical models to predict evaporation rates, is discussed.

RÉSUMÉ — La dispersion des gouttelettes d'aérosol au-dessus d'un couvert forestier est modifiée non seulement par la dimension des gouttelettes, mais encore par des facteurs météorologiques comme la vitesse du vent et la turbulence atmosphérique. Cette dernière dépend des propriétés aérodynamiques du couvert, de la topographie locale et du profil des températures prévalentes. La discussion porte sur les effets de ces facteurs et sur leur importance dans des situations pratiques, en insistant surtout sur la connaissance des vitesses d'évaporation. La discussion porte aussi sur la précision des modèles mathématiques actuels pour prévoir les vitesses d'évaporation.

INTRODUCTION

The dispersal of spray droplets released from aircraft is affected by both aircraft and atmospherically induced factors. The influence of aircraft wake has been discussed in an earlier paper (Drummond 1988). In this paper the influence of the atmosphere above a forest is discussed. The physics of droplet movement and evaporation will be examined along with forest meteorology and the turbulent dispersal of droplets. In this way it is hoped to provide a basis for the later papers in this symposium which discuss mathematical models and draw together many of the effects described here.

PARTICLE PHYSICS

In order to understand how the movement of droplets is affected by environmental conditions above a forest canopy, the basic parameters that influence droplet behaviour must be examined first.

Droplets moving in the air are subjected to the forces of gravity, buoyancy and aerodynamic drag. The aerodynamic forces are characterised by the Reynolds Number (Re) of the droplet, which is a non-dimensional group which is the ratio of inertial to viscous forces, and defined as

$$\mathrm{Re} = \frac{d\ V\ \mu_a}{\varrho_a}$$

Where d is the diameter of the droplet
V its velocity
ϱ_a the density of air
μ_a the dynamic viscosity of air

It has been found that for small droplets where $\mathrm{Re} < 0.5$ (i.e. $< 50\ \mu m$ diameter) the sedimentation velocity of a droplet can be determined accurately by Stokes Law (Green and Lane 1964) which gives

$$\mathrm{drag} = 3\pi\ \mu_a\ d\ V$$

Hence the sedimentation or fall velocity V_s is

$$V_s = \frac{\varrho_d\ g\ d^2}{18\ \mu_a}$$

Where ϱ_d is the droplet density
g acceleration due to gravity

For standard atmospheric conditions, and liquids of density similar to that of water, Spillman (1984a) showed that the above could be simplified to

$$V_s = 0.003\ d^2$$

where V_s has units of cm/sec and d is in μm

For droplets where $\mathrm{Re} > 0.5$ Stokes Law tends to overestimate sedimentation velocity and other descriptions are necessary. Table 1 (adapted from Davies 1966) gives a range of values for V_s for the droplet sizes of interest in pesticide application.

TABLE 1: Sedimentation Velocities and Relaxation Times of Spheres of Unit Density Falling in Air at 20°C

Droplet Diameter μm	Sedimentation Velocity V_s cm/sec	Relaxation Time t_r sec
10	0.30	3.06×10^{-4}
25	1.9	1.94×10^{-3}
50	7.2	7.34×10^{-3}
100	25	2.55×10^{-2}
150	46	4.69×10^{-2}
200	70	7.14×10^{-2}
300	115	1.17×10^{-1}
500	200	2.04×10^{-1}
1000	385	3.93×10^{-1}

Also given in Table 1 is the important droplet parameter t_r, the droplet relaxation time. This is the characteristic time taken for a droplet to adapt to a change in forces, such as occurs when the droplet is subject to a velocity change. This is described by

$$t_r = s / V_o$$

where V_o is an initial velocity of projection
s is the distance required for the droplet to come to rest or stop distance. (May and Clifford 1967)

For droplets moving in air where the density of the droplet is far greater than the density of the air, the relaxation time can also be described by

$$t_r = V_s / g$$

The importance of t can be seen when the trajectories of droplets moving in stable airstreams are considered. The movement can be described by means of a set of differential equations which use t_r as a scaling parameter (Chamberlain 1975). Another area where t_r is important will be described later when the influence of atmospheric turbulence is discussed.

Unfortunately, simple trajectory theory has only a limited role in describing droplet movement in the atmosphere, particularly in turbulent atmospheres. It has however, been used to predict the downwind distribution of spray droplets using what is usually termed the 'hU/V' principle (Gunn et al 1948). The analysis simply considers a droplet released at a height h above a crop, in a steady airstream of velocity U, to be moved downwind and intercept the crop at a distance X. Hence,

$$X = h U / V_s$$

It is this form of analysis which leads to tables such as Table 2 (adapted from Quantick 1985). This method can only provide general conclusions and can often lead to erroneous conclusions when small droplets (usually less than 100 μm diameter) are considered since turbulent diffusion dominates their dispersal. This point will be discussed further when the effect of turbulence above a canopy on droplet dispersal is discussed.

TABLE 2: Predicted Downwind Displacement of Droplets for Given hU Product

hU Product m^2/sec	Droplet diameter μm			
	100	200	300	400
1	3.7	1.4	0.9	0.6
5	18.5	7.1	4.3	3.0
10	37.0	14.2	8.7	6.1
20	74.1	28.4	17.4	12.3
40	148.1	56.7	34.8	24.5
60	222.2	85.1	52.2	36.8
80	296.3	113.5	69.6	49.0

EVAPORATION

As was shown earlier, the movement of pesticide droplets released depends on size. If a pesticide formulation contains volatile components, or a formulation is diluted in a volatile carrier such as water, then the size of the droplets and hence their dispersion characteristics will vary with time of flight and be influenced by factors such as temperature and humidity. Therefore it is essential, in investigating droplet movement, to gain an understanding of the processes involved in droplet evaporation.

In an extensive study of the evaporation rates of pesticide formulations, Dennison and Wedding (1982) measured the evaporation rates of water and oil based formulations using droplets suspended on wires in airstreams. The air velocity was adjusted by a computer controlled system to ensure that droplets were subjected to air velocities equivalent to their sedimentation velocity. Dennison and Wedding concluded that the greatest influence on evaporation rate was initial droplet size. This can be illustrated by reference to their results for a water-based formulation of an insecticide (Orthene). Droplets of 50 μm diameter were fully evaporated in around 2 seconds, 150 μm droplets in 15 seconds, but 420 μm droplets took around 65 seconds to reach this condition.

With water based formulations the relative humidity was found to be the next most important influence on evaporation, although between 20% and 60% relative humidity there was little difference. Oil based formulations showed a negligible influence from changes in humidity. This is hardly surprising since the humidity gradient is the driving force for the evaporation of water but not for other materials. The influence of temperature was considered to be small when compared with other factors. Dennison and Wedding pointed out that this is probably because the normal range of air temperature has little effect on most of the parameters involved in evaporation. A temperature change from 5 °C to 20 °C represents only a 5% change in °K.

As was pointed out by Dennison and Wedding (1982), the parameters which affect the evaporation of falling droplets can be divided into 3 non-dimensional groups. The first group is that which characterises mass transfer rates and is referred to as the Sherwood Number. This can be defined as

$$Sh = \frac{d(dm/dt)_c}{D\,S\,(C_o - C_{inf})}$$

Where $(dm/dt)_c$ is the convective mass transfer rate, m is droplet mass, S surface area, D the diffusion coefficient of the liquid and C_o and C_{inf} the surface and free stream concentrations of the vapour. It was also demonstrated by Dennison and Wedding that the Sherwood Number can also be considered as being

$$\mathrm{Sh} = \frac{2\,(\mathrm{d}m/\mathrm{d}t)_c}{(\mathrm{d}m/\mathrm{d}t)_o}$$

Where $_o$ refers to still air conditions. It can be seen that the minimum value of Sherwood Number is 2.

The two other non-dimensional groups involved in the mathematical description of evaporation are the droplet Reynolds Number (as previously defined) and the Schmidt Number (Sc) defined as

$$\mathrm{Sc} = \mu_a \,/\, \varrho_a\, \mathrm{D}$$

It was found by Frossling (1938) that the general equation which best fitted his data from droplets suspended on wires in an airstream was

$$\mathrm{Sh} = 2 + \alpha \mathrm{Re}^{1/2}\, \mathrm{Sc}^{1/3}$$

Where α is a constant which, for a range of Re, was found to be 0.552

Other researchers (Ranz and Marshall 1952, Goering et al 1972, and Williamson and Threadgill 1974) found similar relationships to be valid for water based droplets with only minor variations. Picot et al (1981) produced a modified form of the above equation to correlate with their results with an oil based pesticide formulation.

Wanner (1980) considered the role of involatile components in pesticide spray droplets. Pesticides are rarely pure compounds and Wanner considered water based formulations to contain an involatile fraction (typically the active ingredient) and water. His data and analysis suggested that water based sprays could be successfully modelled by regarding the initial evaporation rate to be that of water but that after some time evaporation would cease and an involatile core would remain. This conclusion was not reached by Harrison and Parkin (1985), who showed in their experiments that the initial rate of evaporation could not be adequately predicted assuming the volatility of water, since different formulations of the same insecticide diluted to the same dose rate in water, gave different initial evaporation rates. This can be seen on Fig. 1. It is presumed that formulation B contained some highly volatile components since a smaller involatile core remained. It appears that multi-component evaporation should be considered when investigating pesticide droplet evaporation. This is not surprising considering the wide use of such highly volatile solvents such as xylene. The accurate description of complex formulations is not yet available.

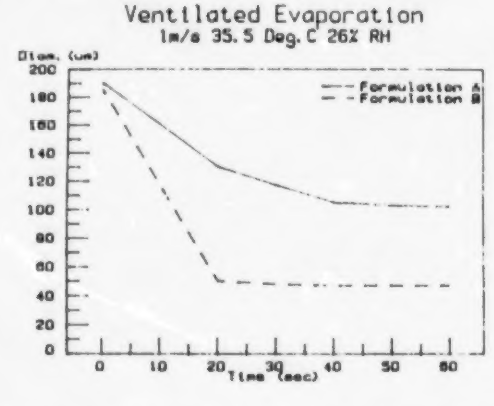

FIGURE 1: EVAPORATION OF WATER BASED FORMULATIONS

Another factor not normally taken into account in laboratory studies was suggested by Spillman (1984b). From data obtained by Hamey (1982) and Whistlecroft (1983) using freely falling droplets, he showed that the variation of diameter with time did not produce a simple relationship and that the data produced two distinct linear relationships. The transition between these areas was equivalent to Re = 4.3. This is shown on Fig. 2. Spillman explained the results as being associated with wake separation and drew on the classic diagrams of Bachelor (1967) to illustrate the point. This is shown on Fig. 3. At low values of Re, flow around a sphere is attached and it was Spillman's contention that under these conditions evaporation occurs from the whole of the surface area of the droplet. This would occur when the droplet had evaporated sufficiently to reduce its Reynolds number below a critical value. Above a critical Re flow is separated behind the droplet and Spillman contended that this reduces the surface area available for evaporation to 79% of the total area (equivalent to 55° semi apex angle as shown on Fig. 3). Above the critical Re further separation has no effect on the available surface area. The critical value of Re did not correspond to that given for rigid spheres (Re = 24). This discrepancy was explained in terms of the deformation of droplets.

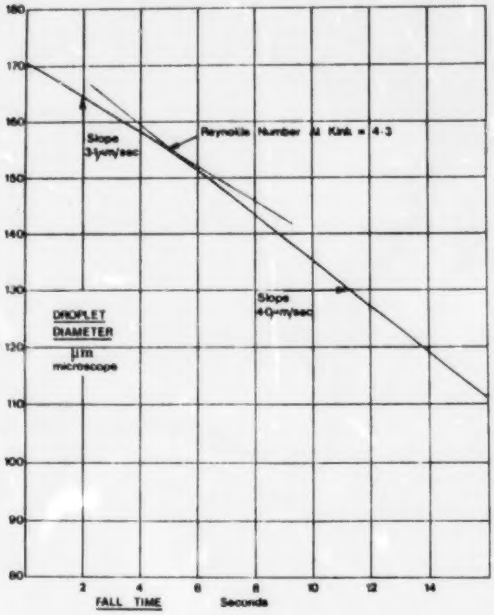

FIGURE 2: EVAPORATION OF FREELY FALLING WATER DROPLETS

The results of Beard and Pruppacher (1970) obtained in a vertical wind tunnel, also showed two distinct linear curves with a transition point which was equivalent to a Re = 2.77 for the conditions used by Spillman. This work was unknown to Spillman.

Spillman also stressed the role that circulation within a droplet can have on evaporation and the influence played by viscosity in modifying evaporation rates. It was in these terms that he explained the anti-evaporant role of molasses and the need to measure droplets evaporating in free fall.

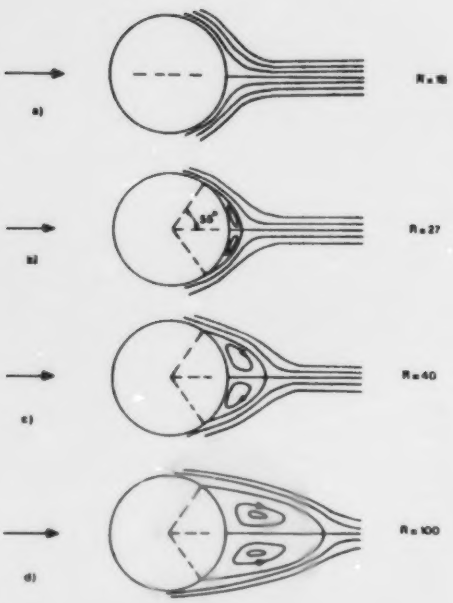

FIGURE 3: FLOW AROUND A SPHERE AT DIFFERING Re

FOREST ENVIRONMENT

Pesticide droplets released from an aircraft above a forest canopy exist in a complex environment. Before examining the interaction between that environment and the droplets, it is necessary to describe the main features of a forest environment as they relate to droplet movement. A set of measurements from a North American coniferous forest will be used to illustrate the general trends. These measurements (Parkin 1975) relate to a typical mature forest stand that is often the target for the aerial spraying of larvae of the spruce budworm, *Choristoneura fumiferana (Clems.)*

The stand, on a level site close to Juniper, New Brunswick, consisted of 60% balsam fir, *Abies balsamea (L.)* and 40% black spruce, *Picea mariana (Mill.)*. The trees, which resulted from natural regeneration following a forest fire in 1911, had a mean canopy height of 16 m. Meteorological measurements were taken at 4 levels extending to 22 m above ground level. Details of the experiment are given by Parkin (1975).

It appeared from the study that incoming solar radiation had a strong effect on the forest environment and particularly on the temperature profiles, hence two distinct cloud covers will be taken as illustrations. These are when skies are clear, and when skies are overcast. By chance, two consecutive days in 1975, June 4th and 5th were typical overcast and clear days and will be used as illustrations of the general trends.

Temperature and Humidity

Temperature and humidity vary diurnally. As can be seen from Fig. 4 under clear skies daytime temperatures were generally higher and daytime relative humidities lower than on overcast days. The converse was true at night. The marked difference in relative humidities may have an effect on the evaporation of water based sprays.

Vertical Profiles

In the study mean wind velocities and temperatures were measured at 21, 16, 9 and 3 m above ground level, allowing wind and temperature profiles to be obtained.

Wind Profiles

Wind profiles for the two typical days are shown on Figs. 5 and 6. Although winds were generally higher on June 5th (Clear skies) a similar profile was obtained. Wind velocities above and within the canopy decrease with height, but below the canopy in the trunk space there was a "bulge" in the profile. The significance of this bulge will be discussed later.

Temperature Profiles

With overcast skies (Fig. 7), temperature gradients above a forest were small. A temperature inversion occurred within the crown during the morning with lapse conditions occurring around midday. The inversion was re-established in the evening. Temperature gradients of the magnitude that occur under overcast conditions appear to be too small to influence droplet dispersal or canopy penetration. Below the canopy there was a temperature inversion throughout the day since the forest floor is always cooler than the crown.

Under clear skies temperature gradients were greater (Fig. 8). In the 5 m above the canopy gradients varied from −1 to +1 °C and in crown gradients varied from −2.5 to +5 °C. A temperature inversion of +5 °C in the canopy will be significant in terms of canopy penetration. Generally, the above canopy inversion at dawn disappeared by 09.00 hrs local time, and the in canopy inversion by 10.00 hrs. The inversion below the canopy remained throughout the day and in some cases the temperature difference between the canopy and 3 m above ground level was 2.5 °C.

Around 18.00 hrs on a clear day inversions are again established in the canopy as the base of the canopy no longer received direct solar radiation. When the top of the canopy no longer received radiation then, because it cooled more quickly than the base, a lapse rate was again established in the canopy. The situation at sunset was therefore, inversion above canopy, lapse in the canopy, and inversion below. This general description above was on occasions upset by changes in cloud cover occurring during the day.

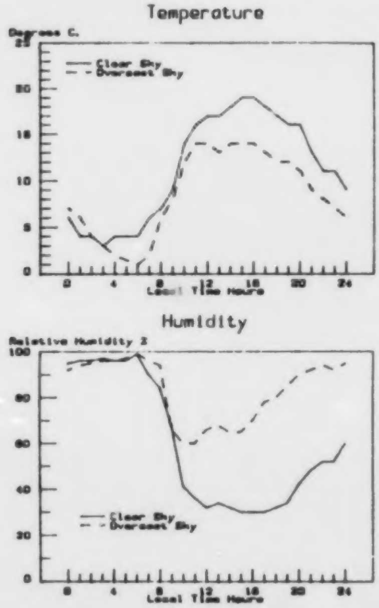

FIGURE 4: TEMPERATURE & HUMIDITY IN A FOREST

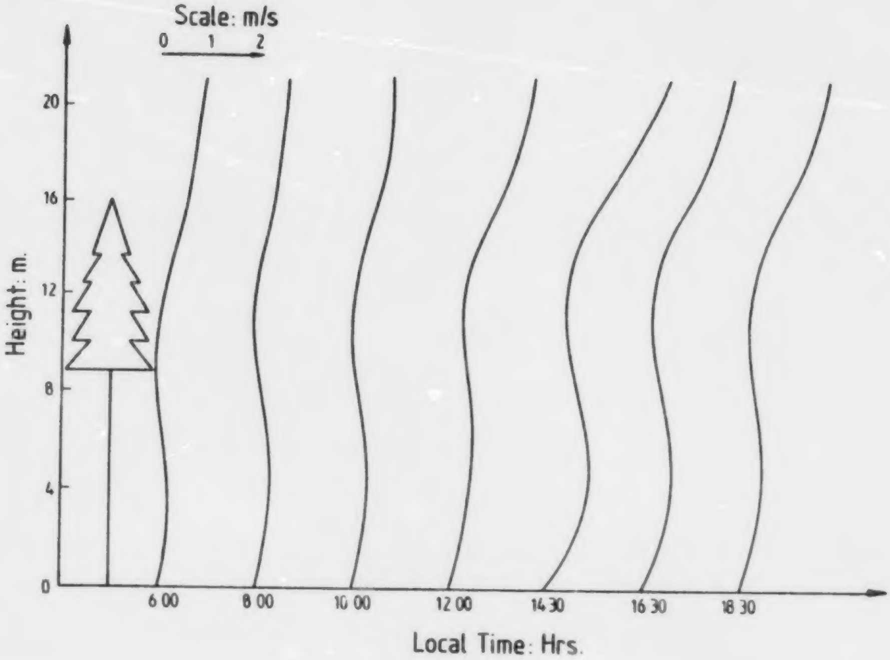

FIGURE 5: WIND PROFILES JUNE 4TH — OVERCAST SKIES

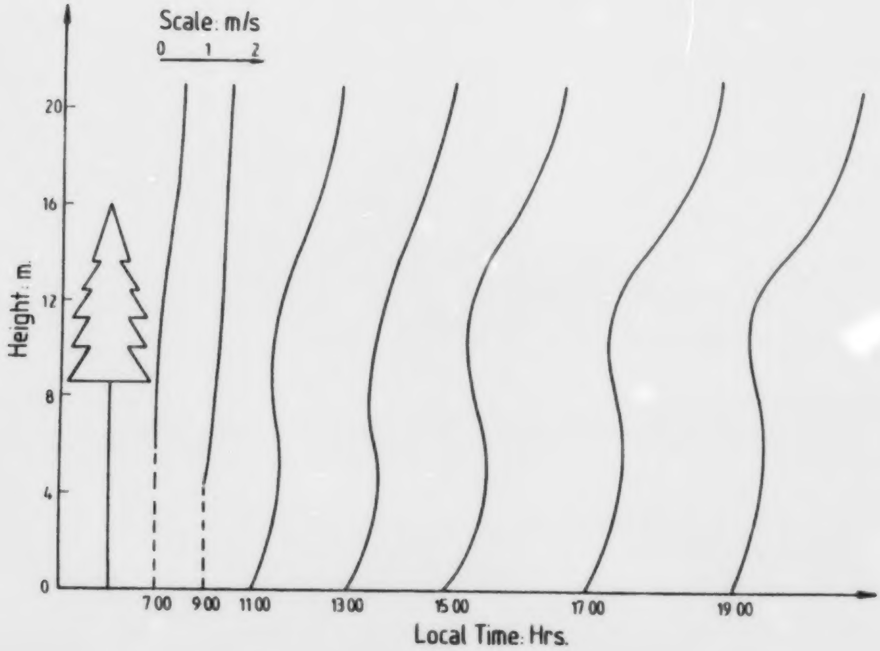

FIGURE 6: WIND PROFILES JUNE 5TH — CLEAR SKIES

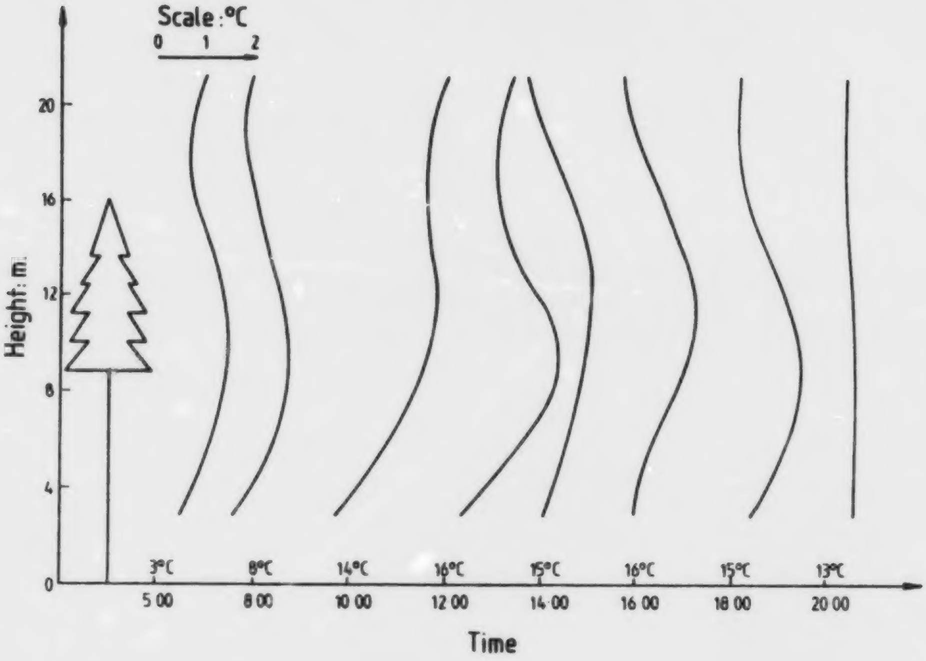

FIGURE 7: TEMPERATURE PROFILES JUNE 4TH — OVERCAST SKIES

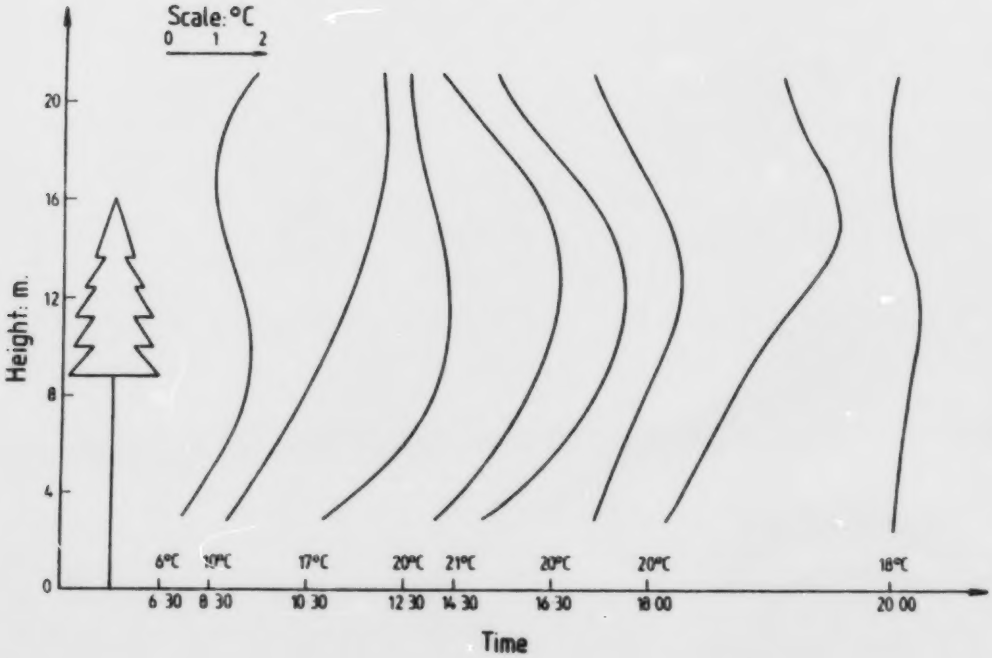

FIGURE 8: TEMPERATURE PROFILES JUNE 5TH — CLEAR SKIES

Topographic Effects

The preceding description and discussion has examined the microclimate of a typical coniferous forest in largely level terrain. Larger scale air movements can also affect spray droplet movement especially, as Ekblad (1983) pointed out, when the terrain is mountainous. In mountainous terrain complex and rapidly changing airflows can occur which must be taken into account in the management of aerial applications.

Topographic effects have been broadly generalised (Geiger 1966) into passive topographic effects where the airflow is modified by topography, and active topographic effects where topography modifies temperature and pressure gradients and these then modify airflow. In the latter case the effects will vary considerably throughout the day and cause pesticide application problems.

A general description of winds in mountains and valleys was presented by Geiger (1966). His description considered two types of wind associated with valleys, slope winds and valley winds. The behaviour of these winds throughout a typical day with clear skies and low winds is given in Fig. 9. We will now examine each of the cases as they occur through the day. (Letters in parentheses refer to the diagrams on Fig. 9.)

Shortly after sunrise (A), upslope winds set in because the valley sides becoming heated by the sun, but down valley winds prevail because the valley bottom is still colder than the surrounding hills. A period of transition then occurs (B) as the valley bottom warms. There is no valley wind but an upslope wind exists. Around midday (C), when the air in the valley heats quickly, upslope and upvalley winds occur. In the early afternoon (D) upvalley winds occur, but there are no slope winds. Late in the afternoon (E), downslope winds occur as cold air from the hills sinks into the valley, but upvalley winds persist. Again there follows a period of transition (F) with no valley winds, but with downslope winds. At dusk (G), downslope and downvalley winds set in as the cold air from the more rapidly cooling hills sinks into the valley. Eventually (H) the down slope winds cease and only downvalley winds occur.

If the valley direction lies North-South then the orientation of the sun warming the valley sides unevenly can cause more complex winds to be set up. If there are persistent winds aloft, then this will also effect the pattern of winds. Measurements of slope and valley winds and their affect likely effect on spray dispersal are given by De Marrais et al. (1968).

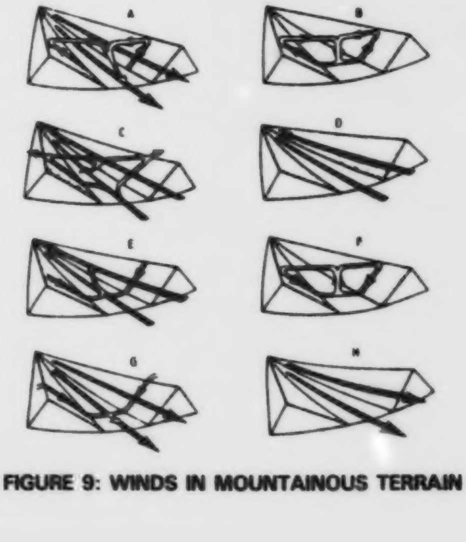

FIGURE 9: WINDS IN MOUNTAINOUS TERRAIN

ANALYSIS OF WIND PROFILES

In order to accurately predict the movement of spray droplets, it is necessary to develop accurate mathematical descriptions of above, within and below canopy wind profiles.

Above A Forest Canopy

Above any surface where there is air movement there is a wind profile varying with height above that surface.

The mean wind profile above a uniform rough surface due to frictional or mechanical turbulence is given by the standard logarithmic profile

$$U = U_*/k \ln\{(z-d)/z_0\}$$

Where U is the mean wind velocity at height z, z_0 is defined as the roughness length d is defined as the zero plane displacement and provides for the effective displacement of the ground plane caused by the rough surface. For short vegetation, such as grass this term can often be neglected, but for tall vegetation it is usually taken as 75% of the crop height. k is von Karman's constant = 0.41 and U_* is the friction velocity which is further defined as

$$U_* = (T/\varrho a)^{1/2}$$

Where T is the vertical shear stress. In the boundary layer above a uniform surface a constant vertical shear stress is assumed and so it follows that the friction velocity is also uniform throughout the boundary layer.

The friction velocity U_* was found by Parkin (1975) to be well correlated to the wind speed measured at 21 metres above ground level in a mixed black spruce and balsam fir stand which was 16 metres high. The friction velocity could be estimated by:

$$U_* = 0.24\ U_{21}$$

The above analysis is strictly true only for neutral stability, where the vertical temperature profile follows the adiabatic lapse rate which approximates to a temperature decrease with height of 0.01 °C per m. Where conditions deviate from neutral or near neutral stability we must examine the effect of temperature profiles on both the wind profile and atmospheric turbulence.

The two most important parameters which describe atmospheric stability are Richardson Number and Monin-Obukov length. The Richardson number is a non-dimensional parameter which determines the relative importance of free and forced convection. It can be used as a measure of the stability of air close to the ground and is defined as

$$Ri = g/T\ (dT/dz)\ /\ (dU/dz)^2$$

where T is the temperature at height z

Positive values indicate stable conditions, negative values unstable. It is similar to the empirical parameter Stability Ratio (S.R.) (Yates et al. 1974) which has been used in much spray application research. This can be defined as

$$S.R. = \frac{T_{(10)} - T_{(2.5)}}{U_{(5)}}$$

The values in parentheses refer to measurement height.

The Monin-Obukov length L can be interpreted as the height above which free convection dominates. This is defined as

$$L = -(U_*^3 \, Cp \, \rho_a \, T) \, / \, (k \, g \, H)$$

Where Cp is the specific heat of air
T is absolute temperature
H is vertical heat flux (+ve upwards)

Procedures for its calculation are given by Webb (1965). The wind profile equation can be modified to incorporate atmospheric stability by the addition of a linear term for stable to slightly unstable conditions (Thom 1975).

$$U = U_*/k \, \{\ln (z\text{-}d)/z_0 \; + \; 5(z\text{-}d\text{-}z_0)/L)\}$$

Other more complex modifications of the wind profile equation exist for unstable conditions. These also depend on Richardson Number and Monin-Obukov length (Webb 1970 and Dyer 1974).

The effect of atmospheric stability on turbulence and the profile of wind above a rough surface can be seen on Fig.10 where examples of the wind profiles are given for the three basic classes of atmospheric stability (Thom 1975). Also shown on Fig.10 are simplified representations of the size of turbulent eddies as they relate to height above the crop and atmospheric stability. A simple explanation of the effect of height temperature profiles on eddy size can be made if eddies are conceived as being circular with diameters equivalent to the mixing length (kz). In this case they rotate at a uniform tangential speed equivalent to the friction velocity U_*. In unstable or temperature lapse conditions vertical motions are enhanced by buoyancy effects and the eddies are elongated in the vertical direction. The converse is true in stable or temperature inversion conditions.

In a Forest Canopy

The wind profile within a canopy can be described by an exponential form:

$$U = U_h \, e^{-\beta(1\text{-}z/h)}$$

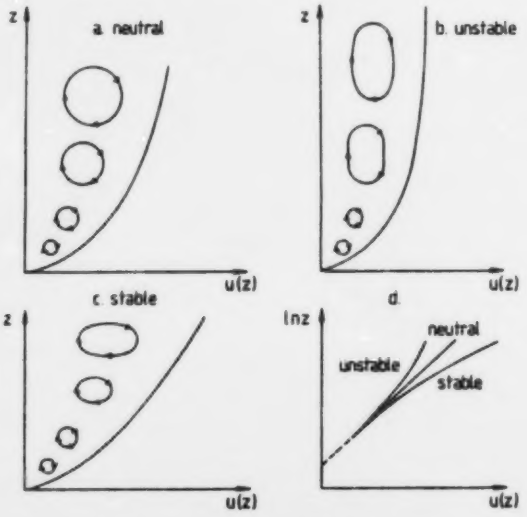

FIGURE 10: EFFECT OF ATMOSPHERIC STABILITY ON TURBULENCE AND WIND PROFILE

Where U_h is the wind speed at height h which is the top of the tree canopy. β is a constant.

An approximate form of the above equation which is usually used (Landsberg and James 1971) is

$$U = U_h \, \{1 + \beta(1\text{-}z/h)\}^{-2} \quad \text{for } z<=h$$

Oliver (1975) found that for a pine forest that varied between 2.5 and 3 and that for a large range of conditions the value 3 could be used.

Below the Canopy

Many researchers have noted variable "bulges" in trunk space wind profiles. (Landsberg and James 1971, Oliver 1971, Parkin 1975, etc.). Although bulges can result from forest edge effects and some "blow-through" phenomenon, bulges have been detected at sites where there was considerable fetch. Oliver (1975), considered the bulges to be associated with intermittant convective plumes. Observations of smoke trails from smoke canisters ignited below forest canopies (Oliver 1973 and Parkin 1975), have shown that under lapse conditions convective plumes can occur. Once a large eddy has left a canopy air has to be drawn in from around the trunk space to replace it. Oliver (1975) considered this to be the explanation of the trunk space bulge and although no generalised theory has been produced for the below canopy profile, Oliver (1975) showed that the ratio of below canopy to above canopy velocities increased with decreasing wind speed and was closely related to Richardson number with increasing instability causing increasing trunk space bulge ratios. Ratios varied from 10% under stable conditions to 40% under unstable conditions.

Perhaps the most important influence the trunk space bulge has on droplet dispersal is not its direct effect on spray droplets, since most targets for pesticide are in the canopy, but the fact that the bulge is usually the result of convective plumes. These plumes will disrupt the movement of spray and cause uneven deposition.

ATMOSPHERIC TURBULENCE

So far our examination of air movement has, in the main, been restricted to horizontal components and mean values. The fate of pesticide spray droplets, however, is strongly influenced by vertical air movements and transitory effects and so an understanding of the levels of turbulence above and in a forest canopy is required.

The movement along the wind is usually described as being in the x direction, the direction across the wind y, and vertically being the z. The corresponding air velocities are designated u,v and w. Turbulence levels are usually measured by taking the root mean square (R.M.S) velocities normalised to time averaged horizontal mean velocity. These values are designated turbulence intensities. The vertical turbulent intensity i_z is defined as

$$i_z = \frac{(\bar{w}'^2)^{1/2}}{\bar{U}} \quad \text{or} \quad \frac{\sigma_w}{\bar{U}}$$

Where w' is the vertical velocity fluctuations
σ_w is the variance of the vertical velocity fluctuations

Similar turbulent intensities are defined for the x and y directions.

Values of i_z can be measured directly using vertical anemometers (Crabbe et al. 1982) or be estimated from wind profiles (Bache 1975). Where turbulence is homogeneous the friction velocity can be used as an indicator of turbulence since

$$i_z \simeq U_* / \bar{U}$$

Values of i_z over New Brunswick forests were estimated by Parkin (1975) using the profile method and varied between 0.105 and 0.205. Crabbe et al. (1983), also examining New Brunswick coniferous forests, measured i_z values between 0.15 and 0.32 by direct measurement using 3 axis anemometers and vector vanes.

Turbulence and Droplet Dispersal

The dispersion of droplets is dominated by turbulence if the velocity fluctuations due to turbulence exceed the sedimentation velocity. The parameters which can be taken as indicators of velocity fluctuations are U_* or σ_w. Using the results of Parkin (1975) the effect of wind speed on U_* can be tabulated and compared with the droplet diameter that has an equivalent sedimentation velocity. This indicates the effect of mean windspeed on the turbulent dispersal of droplets, since droplets with diameters smaller than the diameters shown on Table 3 will tend to be affected by turbulence and droplets larger than this size will tend to be unaffected by turbulent eddies.

TABLE 3: Relationship between Dropsize and Windspeed over a Forest on Droplet Dispersal by Turbulence and Sedimentation

Wind Speed $\bar{U}$ m/sec	Friction velocity U_* m/sec	Droplet Diameter $(V_s = U_*)$ μm
1	0.24	96
2	0.48	150
3	0.72	204
4	0.96	258
5	1.20	311

As can be seen from Table 3 at higher wind speeds droplets with diameters as big as 300 μm, which in agricultural crop spraying are regarded as "large", can be effected by the high levels of turbulence that are generated above a forest canopy.

Cramer and Boyle (1973) developed a criteria for establishing the dominance of either turbulence or sedimentation. They considered "large" drops to be when $V_s > 3U_*$ and "small" drops to be when $V_s < \frac{1}{3}U_*$. This criteria is shown on Fig. 11 again using the data of Parkin (1975).

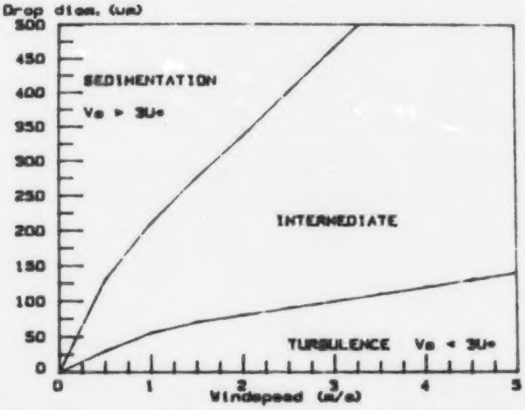

FIGURE 11: EFFECT OF WINDSPEED ON DROPLET DISPERSAL

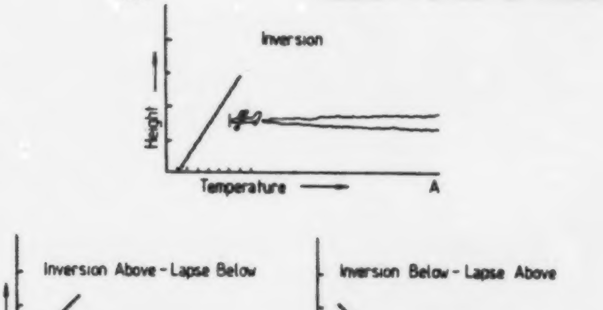

FIGURE 12: EFFECT OF ATMOSPHERIC STABILITY ON DROPLET DISPERSAL BY TURBULENCE

The value V_s/U_* has been defined as a dispersal number (Lawson and Uk 1379). The larger this value the more sedimentation will dominate, the lower the more turbulent dispersal will dominate. In terms of Table 3 the droplets specified in the last column will be at a dispersal number of 1.

Also of interest in determining the influence of turbulence on droplets is the time scale of the turbulent eddies. Eddies with time scales less than the relaxation time for a particular droplet size will not affect droplet movement. Hence it is possible for heavy particles with long relaxation times (t_r) to remain unaffected by turbulent eddies of short duration. Eddies should have durations in excess of the droplet relaxation time to dominate droplet dispersal. Few studies to date have investigated turbulent spectra in relation to droplet dispersal. Work is currently being carried out at Cranfield on investigating droplet dispersal in relation to turbulence spectra.

Atmospheric Stability & Turbulent Drop Dispersal

Atmospheric stability, as was pointed out earlier, alters the vertical scale of turbulent eddies. Under stable conditions (temperature inversion) the vertical extent of eddies is reduced and the vertical disperson of "plumes" of small droplets also reduced. Fig. 12 (adapted from Quantick 1985) shows the effect some atmospheric stability conditions have on droplet dispersion in turbulence. The inadvisability of spraying small droplets above a temperature inversion can be seen. The data of Yates et al. (1974) supports this conclusion since downwind deposits increased with increasing S.R.

As was pointed out by Lawson (1979), under conditions of strong stability vertical air movement can be severely restricted and almost completely suppressed. In these situations drift cannot be easily predicted, both in terms of quantity or direction of movement.

CONCLUSIONS

The movement of spray droplets, even neglecting aircraft wake effects, is a complex process. In forest spraying the process is made even more complex by the elevated source and rough surface providing difficulties for analysis and the size of the target providing difficulties for experimentation.

Although the physics of droplet movement is well understood it is clear that evaporation of droplets, and particularly of multicomponent pesticide formulations, is not well described by current theory. Improvements in both theoretical and experimental techniques are required to provide accurate relationships for integration into mathematical models. Experimental techniques which can allow the measurement of evaporation in free fall are required.

Studies in forest energy budgets and pollution, along with more recent studies on particle dispersion above forests, have begun to provide forest spraying researchers with much useful meteorological information, but it is clear that there is still much experimental and theoretical work to be done. Just under a decade ago a forest meteorology workshop held in Ottawa (Hutchison 1979) concluded that "Lack of knowledge and understanding of the mechanisms of turbulent exchanges of sensible heat, mass and momentum within forests and across forest-atmosphere interfaces is, without doubt the most critical current problem of forest meteorology". Although some progress has been made, it would appear that much has yet to be done, particularly in describing effects in areas of complex terrain and providing information on the spatial and temporal variation of turbulence.

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THE PRODUCTION, TRANSPORT AND IMPACTION OF LARGE DROP SIZE HERBICIDE SPRAYS

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ABSTRACT — Optimum drop size for most effective control of unwanted plant species by herbicidal sprays lies somewhere in the range of 100-200 microns as topically applied, monodisperse drops. However, all but a few experimental atomizers available today produce drops in a skewed (towards the small end) Gaussian distribution ranging from a few microns diameter to several hundreds. That the small drops are hazardous to non-target organisms and large ones wasteful of chemical is widely acknowledged. But, until more effective cut-off of the large and small drops is accomplished, there is little hope of improving application efficiency. Thus, the selection of drop size must be based on safety from damage by drifting herbicides, which at present is poorly resolved, by moving the entire spectrum of drop size towards the large drop end. While biologically more effective, small drops also contribute to drift losses and potential for non-target damages. Selection of a proper size must take into consideration both these requirements.

RÉSUMÉ — La dimension optimale des gouttes d'un herbicide en aérosol pour l'élimination des espèces végétales indésirables se situe quelque part dans la plage des 100-200 microns, qu'il s'agisse d'applications topiques ou de gouttes monodispersées. Toutefois, à l'exception de quelques atomiseurs expérimentaux, tous les atomiseurs actuels produisent des gouttes dont la dimension suit une distribution gaussienne (biaisée vers le bas) depuis quelques microns jusqu'à plusieurs centaines de microns. Il est notoire que les petites gouttes sont dangereuses pour d'autres organismes que l'organisme cible et que les grosses gouttes sont une perte de produits chimiques. On a cependant peu d'espoir de rendre l'épandage plus efficace avant d'avoir réussi une meilleure élimination de ces deux types de gouttes. Le choix de la dimension des gouttes doit donc se faire en fonction de la sécurité, eu égard aux dommages causés par la dérive des herbicides qui est mal résolue présentement, en déplaçant tout le spectre de la taille des gouttelettes vers les grandes dimensions. Bien que des gouttelettes plus petites soient biologiquement plus efficaces, elles contribuent aussi aux pertes dues à la dérive, tout en pouvant endommager d'autres espèces que la cible. Le choix d'une bonne dimension pour les gouttes doit tenir compte de ces deux exigences.

INTRODUCTION

Large drop size pesticide sprays, defined for the purpose of this text as those greater than 450 μm vmd (microns, volume median dia.) are widely used for herbicide applications by aircraft in agriculture and forestry. This is in contrast to much smaller drop size vmds of 25 to 50% of this size commonly used for insect and plant disease control. Airborne movement or loss of herbicides during and following an application may be small but significant, consisting of the small drop size end of the size range being produced (Akesson 1974). All commercially available atomizers generate a range of drop sizes which depends on the type and operating characteristics of the atomizer and physical characteristics of the liquid being atomized (Akesson 1984a). During an herbicide application the small drops (defined as those < 100 μm) can readily be moved by ambient air motion during the application. Further losses can also be sustained after the spray is deposited where movement can occur in the form of vapor and also as fine particles of toxicant on plant detritus and soil. Prevailing winds may carry toxicants from the initial spraying, as well as during a period following application, into non-target areas where crops and gardens as well as waterways may be damaged or contaminated. It is this problem of potential drift and damage from herbicide applications which has dominated the thinking in respect to herbicide application techniques (Stewart 1976).

HERBICIDE ACTIVITY AND DROP SIZE

Biological effectiveness of herbicides has been shown by many observers to be affected by the drop size and active chemical concentration of the applied sprays. Ennis (1963) showed that plants (soybeans, flax, sugar beet and wheat) sprayed with 2,4-D, a translocated herbicide, had more stem curvature and showed reduced yield as drop size was reduced from 500–600 μm to 100 μm dia. using a monodisperse applicator. Solution concentrations of both 3% and 10% for the different size drops displayed similar yield reduction with the 100 μm drops. Behrens (1957) reported that a minimum of 10-12 drops/cm^2 was required for maximum plant response and he felt drop coverage (spacing) was more important than size of the drops within the range of 100 to 500 μm dia. Ennis suggests that even smaller drops would have greater effectiveness and felt that the better coverage plus low drop concentration prevented rapid "burn" of the plants and facilitated entry of the 2,4-D and 2,4,5-T to plant tissue. But, he also acknowledged that for field applications consideration for spray drift would require that larger drop sizes be used.

Similarly, McKinlay (1973) found the response of sunflower to paraquat was significantly enhanced with 100 μm drops having greater phototoxicity effects (tissue damage) than 350 μm drops.

Tests with two levels of concentration showed the higher concentration such as used with reduced volume application produced greater toxic response.

More recently Newton (1984) indicated that in field tests sprays having a vmd of greater than 400 μm were less responsive on various woody species than smaller drop sizes. Prasad (1987) conducted a detailed study in the greenhouse with triclopyr, glyphosate and hexazinone. He sprayed 4 month old seedlings of birch, alder and aspen using a monodisperse atomizer for drops of 155, 335, 465 and 665 μm dia. Evaluations after 3 weeks showed the 155-335 drop applications were more biologically effective than the larger sizes. As with Ennis's earlier work with 2,4-D Prasad attributed these results primarily to biological response of small amounts of active herbicide uniformly applied to the individual leaf surface. Triclopyr and glyphosate are translocated herbicides while hexazinone is a contact type material. As would be expected the latter showed greater response to the smaller drops than did the translocated materials. Note that Prasad applied the same dosage of ai but not in the same numbers of drops. Thus, coverage was different for the different size drops. The use of surface active adjuvants with herbicides has been shown to improve spreading of drops and penetration of plant cuticle and tissue (McWhorter 1982). The use of a surfactant can in part improve the spreading and redistribution of chemicals applied in large drops, thus, making possible use of the safer large drop sprays. An additional function of surface active materials is to reduce the rebounding of drops from plant surfaces and increase the potential for break-up of large drops striking leaves, twigs and needles. Hess (1974) using a scanning electron microscope showed that large drops over 500 μm dia. shattered on impact with surfaces and hairs on leaves forming many more small drops that give additional coverage of the leaf. Smaller drops (< 200 μm dia.) were less prone to shatter and tended to cling to leaf hairs without reaching the active leaf surface. This observation could indicate that larger drops traveling at greater velocities could be helpful in penetrating brush canopy and with shattering produce a significant increase in coverage through generation of many small drops.

Armstrong (1980) used two drop size sprays to spray small (approximately 3 m tall) white fir trees in the laboratory. Drop size was estimated at 150-200 μm vmd for the smaller size spray and 300-400 μm vmd for the larger drop size. Results indicated equal volumes of spray from the two sizes were found at various areas of the trees, but with the smaller drops better coverage was found due to the greater number of drops available. Deposits tended to be higher, for both sizes, in the tree crown and on the side facing the wind (Fig. 1).

Bouse (1969) used what had best be called "giant drops" for brush control in a multi-storied over-grown range area. He found that in the size ranges he used varying from 700 to 3800 μm vmd, no significant difference could be found in penetrations by volume of spray or numbers of drops. These were measured by collection of drops on kromekote cards placed at 3 levels, one, at the top of the overstory canopy approximately 12 m above the ground; two, between the upper and secondary canopy approximately 4.55 m above the ground and; three, at the ground level. Percent penetration by volume of spray averaged around 21% (of the amount deposited at the top level) as was found between the stories, and 5.4%, which penetrated all the way to the ground level. No mention was made of the herbicide being used or the level of brush control being achieved.

In California restricted use herbicides were identified in the early 1950's (later reclassified as restricted materials) and large drop size producing spray systems were required by state regulation for their application. These regulations initially included the phenoxy herbicides, later amended to include propanil, paraquat, picloram, dicamba, phenols and cresols and Molinate. The restricted materials require county level permits for their use and for all liquid sprays specific equipment and operation conditions are required for both aerial and ground application. For fixed wing aircraft the jet nozzle (simple orifice, no whirl core) of 0.159 cm (1/16 in.) dia. or larger directed with the airstream and operated at not over 276 kPa (40 lb/in^2) is specified. For helicopters operating at 96 km/h or less, the 0.159 cm orifice may have a #46 or larger whirl core added to provide better spray atomization at the lower air speed. Spray drop size for the jet nozzles is in the range of 800 to 950 μm vmd, while the addition of the #46 whirl core reduces this to 450-550 μm vmd at the reduced airspeed. These nozzle systems have been used for about 35 years for California restricted herbicides. While there is little doubt that wider more uniform swaths and better control efficacy could be achieved with smaller drops the potential for damage under California multicrop agriculture is too great to permit the use of smaller drop size sprays for highly active herbicides (Akesson 1984b).

A brief discussion should be included here on the many studies done on drop size and forest insect control. Early forest spray work has been summed up by Barry (1984) and Ekblad (1984). Field tests indicated that 87% of the drops found on Douglas fir needles were very small aerosol size drops of 1 to 16 μm dia. Also on Eastern spruce budworm larvae drops of 6 to 15 μm dia. were dominant at 76%. In other tests using sprays of around 300 μm vmd, 86 to 94% of the drops on the needles (Douglas fir) were less than 61 μm and 40 to 71% were less than 16 μm dia. Since the initial drops released by the aircraft are so much larger (200-300 μm vmd) than what is caught by the fir needles it raises the question of whether larger drops are shattering, evaporating or just how are sufficient small drops generated to produce the coverage found in the trees (Wedding 1984). It is also to be noted that deposit in the fir trees is largely confined to the upper crown or to the upwind side of the tree where sprays are rapidly filtered out by the highly efficient needles of the tree (Armstrong 1984, Kristmanson 1984).

In agricultural spraying by ground equipment, Burt (1970) and others summed up the considerable field test work that had been done with ULV (ultra-low-volume) sprays on various crops, cotton, soybean, and corn. Burt using narrow size range drops from a spinning disc atomizer of 140, 200 and 300 μm vmd found satisfactory insect control for the smaller drops but inadequate coverage gave poor boll weevil control, on cotton for example, with drops of 300 μm vmd. The implication here is that while volume of toxicant deposited may be the same, the difference in coverage or drops/unit area reflects the same comment made by Behren's earlier that drops/unit area were more important than size of the drops. This could be even more important for insect and fungi control than for weed and brush control. Burt concluded that drift studies showed sprays of 140 μm vmd or smaller produced significant drift-loss and suggested that sprays even by ground equipment should be greater than 140 μm vmd.

Probably the most widely accepted aerosol applications are those used for mosquito control. Akesson (1986) applying Scourge® (a pyrethroid) by aircraft found sprays in the range of 10-15 μm vmd to be equally as effective as applications of 25-30 μm vmd for adulticiding under temperature inversion conditions. But a temperature inversion is essential to hold the aerosol down near to the ground so that flying mosquitoes can contact the drops in the aerosol cloud. Due to difficulties in obtaining the 10-15 μm vmd size by aircraft equipment it was concluded that a 30 μm vmd aerosol was as small as was practical for use by the California Districts for aircraft control operations. It is interesting to note that spraying for Tsetse fly control as reported by Coutts (1980) indicates a 30 μm vmd aerosol has been proven in field tests to be more effective than larger drop size ranges, while still being manageable with aircraft. But, also is best performed under inversion type weather.

PHYSICAL PROCESSES IN DROP DEPOSIT

The physical aspects of drop deposit has been examined by a number of investigators with a monograph edited by Elliott and Wilson (1983) presenting a good summary of this aspect of pesticide spraying. Spray drops released from the aircraft have initial velocity imparted to them by the shed vortex of fixed wing or helicopter in flight. While considerable discussion has centered on the presumed ability of the helicopter rotor to cause a large downward displacement of air it is to be noted that the air displacement of any aircraft is dependent upon the weight of the aircraft, the velocity through the air and to a much smaller degree the form of the wing or the characteristics of the helicopter rotor. Investigations by Yates (1974) of air velocities beneath a small (1340 kg) helicopter sprayer showed that maximum vertical air movement was induced by the helicopter at hovering. At 29 km/hr forward speed the maximum vertical air pulse velocity was 14 km/hr and at 72 km/hr speed, the maximum pulse was 13 km/hr, both flown at 3.6 m above the anemometer. At 9 m above the anemometer the maximum pulse was 13 km/hr at 29 km/hr forward speed and dropped to 6.4 km/hr at 72 km/hr speed. Obviously a faster flying fixed wing aircraft of the same weight would produce less downwash, but larger multi-engine aircraft frequently used in forest spraying would produce a greater vortex effect although this would likely be tempered by a greater flying height required.

After release from the aircraft, drops move toward the ground under the influence of gravity as sedimentation and under the influence of aircraft vortices and ambient wind velocity to affect impaction of drops. In simple terms which in no way reveal the very complex picture of drop sizes and eventual coverage on a specific plant or insect target, the sedimentation is governed by Stokes Law where V_s is settling velocity, ϱ_ℓ and ϱ_a are liquid and air density, g is gravitational constant and η is air viscosity and d is droplet dia. Thus:

$$V_s = g\, d^2(\varrho_\ell - \varrho_a)/18\,\eta$$

The drop velocity and the mass deposition become a function of drop dia. squared for the range of drop size of 1 to perhaps 200 μm drop size. But number deposition is an inverse function of drop dia. Greater numbers occur from a given volume release as drops are reduced in size, the number being a function of d^3 with 8 times more numbers of drops resulting from a reduction in drop dia. by 2.

The impaction efficiency E, defined as % numbers impacted/numbers available can be related to (d) the drop dia., (v) the drop to object velocity, (ϱ) drop density, (μ) fluid viscosity and (D) object dia. Thus:

$$E(f) = d^2 v\, \varrho / D\mu$$

The symbol f denotes the form or shape of the object as flat, round or other which influences the manner and efficiency of deposition. The rate of mass deposition by impaction is directly a function of drop velocity (or wind velocity for drops less than about 50 μm drop dia.) and an inverse function of object frontal width. But again the rate of number deposition will be increased by the total numbers of drops available, a function of drop size. Limitations on minimum drop size for impaction on plants and insects is such that drop size and object frontal width should not go below a ratio of unity. Thus drops smaller than the object tend to flow around the object instead of impacting on the plant targets. Object size varies from perhaps one to several thousand mm, from plant stems to large leaves (Cramer 1976, Dumbauld 1984).

Obviously, the functions of sedimentation and impaction will have various degrees of influence on a given spray usage. For herbicides where plant targets are aimed for, drops of 300 to 400 μm, primarily affected by sedimentation and not impaction would appear to be most advantageous to use for forest brush control from the viewpoint of physical application. However, it is to be noted that biological response favors the use of smaller drops and coverage may dominate the effective result of a given spray application and not the drop size per se. Although applications of sprays in drop size ranges less than 300 μm vmd may be found more effective, the choice of a size range for a given application job returns to the problem of drift loss of the herbicide from the application area (Akesson 1976).

ATOMIZERS FOR HERBICIDE APPLICATIONS

Hydraulic pressure atomizers for aircraft spraying are customarily supplied by manufacturers in a wide range of nozzles used for such things as cooling towers, spray drying, oil burners and others including pesticide spraying. Fig. 2 shows several basic type nozzles as available from commercial manufacturers. From left to right these are: jet, or simple orifice; hollow cone, disc-core type; hollow cone, tangential entry type; solid cone, fan and deflector fan. These are all available in a range of flow-rated sizes approx. 0.2 to 10 ℓ/min; the deflectors to as high as 350 ℓ/min at specified operating pressures 70 to 415 kPa. All of these shown, as well as similar design speciality nozzles, are used on aircraft for pesticide spraying. The choice used by a given operator appears to be more of a personal preference than any basic advantage one has over the others. Materials such as hardened stainless steel and ceramic are used for longer tip life but wear is rapid especially with particulate sprays such as clays and other materials (Akesson 1974).

Drop size produced by the pressure nozzles is related to liquid throughput which increases drop size as flow is increased and to pressure applied which acts inversely to reduce drop size. Thus, larger drop size nozzles have been devised simply by reducing the pressure applied and increasing the nozzle orifice to maintain a given flow rate. Another technique for producing large drop sizes is by means of an additional orifice cap on the nozzle discharge which is designed to re-circulate the initial spray and agglomerate small drops into larger ones. This latter device is called the Raindrop® or RD nozzle. No significant narrowing of the drop size range is apparent with either the LP or RD nozzles, the basic Gaussian distribution is moved upward in size range which reduces the volume and number of small drops (Yates, 1984).

One of the commercially successful devices for narrowing the drop size range of large drop size sprays and actually reducing the amount of spray in small drops is the Microfoil® device (Fig. 8). Here hypodermic needles with a 0.33 mm inside diameter are fitted into the trailing edge of a small airfoil section such that the air flow over the section approaches a laminar condition. This smooth air flow accelerates the drops coming from the tubular orifices, under Raleigh breakup, without causing air shear shatter of the drops. Drop size produced under Raleigh atomization conditions is approximately equal to twice the orifice diameter. Thus, the drops from the 0.33 mm tube are of the order of 800 to 1000 μm but with a small amount in sizes above and below this. Air speed will start to break up the drops at around 100 km/h hence the device is useful only when operated below this speed. Yates (1983) examined this technique for producing drops of a more useful smaller size and developed a similar airfoil section but with orifices in a strip of metal inset in the trailing edge of the airfoil. He found that pulsing the spray liquid could help to produce a nearly monodisperse size distribution, but even without the pulsing the range was significantly reduced. The primary difficulty for such a system is the very small orifices required to make 250 μm drops, roughly 125 μm diameter.

Other types of atomizers such as rotary screen, disc or sintered metal are designed primarily for small drop size sprays of less than 250 μm vmd. The drop size produced by rotary atomizers in an airstream is a function of the peripheral velocity of the screen or rim of the disc, the airstream (shear) normal to the screen axis and the flow rate or throughput of spray liquid. Rotary atomizers can be operated under no airstream conditions to produce a very narrow drop size range. But placing these in an airstream and rotating them with an air blade produces a break-up of drops much the same as for the hydraulic nozzles, or a basic skewed Gaussian distribution (Akesson 1978).

Drop size range produced by the hydraulic nozzles ranges from vmd of around 100 μm to as large as 2 or 3 mm. Figs. 3 and 4 shows vmds at different flow rates for fan and cone nozzles operated at 2.76 BAR (276 kPa) and for the fan (Fig. 3) at 3 different positions of discharge to a 161 km/h air stream, with two positions for Fig. 4. The solid lines are for water while the dashed lines are for a cottonseed and petroleum solvent mix at 85 and 15% respectively. These graphs show the increase in drop size as flow rate is increased and also that maximum drop size occurs at 0° discharge angle to the airstream (Yates 1984). Data for these graphs was obtained with a Particle Measuring System Imaging Analyzer in a low turbulence wind tunnel. Fig. 5 shows a bar graph distribution of drop sizes for a D6 (0.24 cm) jet nozzle at 0° to a 161 km/h airstream and operated at 276 kPa pressure. The nmd is indicated at < 56 μm and the vmd at 861. The relative span (a measure of size range) is shown as 1.58. Fig. 6 shows drop size distribution for a D6-45 nozzle, 0.24 cm orifice with a #45 whirl core. Here the nmd is 82 μm and the vmd 244 μm with an RS much narrower than the jet at 1.19. Fig. 7 is for an AU 5000 Mini-Micronair rotary atomizer operating at 15 ℓ/min and around 8000 rpm in a 161 km/h airstream. The nmd was less than 56 μm, the vmd 122 and RS 0.99. The relative span is found by subtracting the drop size at 10% accumulated volume from the size at 90% accumulated volume and dividing by the vmd or 50% volume size. Thus, it can be seen that the D6-45 cone nozzle produced a larger RS or wider drop size range than did the rotary type operated under the specific conditions (Yates 1984). In general the RS becomes smaller as drop size is decreased for any atomizer. There are several rotary atomizers being offered for sale to aircraft operators, but the Micronair is the earliest and probably most durable of all that are presently available. The rotaries are normally used for producing small drop size sprays for such jobs as forest insect spraying and can produce a vmd of around 75 μm at low flow rate (1/2 ℓ/min) and 12 to 14,000 rpm. They also have been used experimentally for herbicide spraying producing drops of around 1000 μm vmd when operated at around 2500 rpm and discharging 113 ℓ/min each.

Spray adjuvants and additives have been used for increasing drop size of the discharged spray to reduce drift losses. There is no evidence to suggest that the Gaussian distribution of drops is altered by these additives, hence it is of questionable value to use an additive at increased cost and inconvenience when drop size can well be increased by use of low pressure larger volume flow hydraulic nozzles. Butler (1969) did a detailed study on drop size produced by a wide variety of viscous spray formulations using various natural and synthetic polymers as well as phase crowded emulsions. His test work indicated drops up to 7500 μm vmd could be produced with the usual shifting of the Gaussian drop distribution. But in none of the tests did he show an elimination of small drops (under 100 μm) which left a small but significant amount available to drift and potential damages. The most widely used drift reduction additives are various forms of water soluble polymers. These may be polyvinyl, polymide copolymer, alkyl epoxide, polyarylanide and polysaccharide. Bouse (1986) examined 6 different formulations of polymers in wind tunnel studies to determine the effect on drop size and size range of the polymers added to water based sprays with 0.1% of a surface active material, Rohm and Haas Triton X-100. Considerable variation in concentration and viscosity of the formulations was found. Some were very effective at increasing drop size while others were not. Overall, however, the normal or Gaussian distribution from the pressure nozzles tested was not altered from that of the spray fluids without polymers but simply moved upward in size with consequent reduction (in most but not all cases) in small driftable drops.

DRIFT LOSS OF HERBICIDE SPRAYS

Studies have been conducted since the 1960's by various research groups on the transport and loss of pesticide chemicals during and following application by aircraft and ground machines to field, row and orchard crops (Yates 1973, Maybank 1984). The mass rate of movement of spray drops away from the discharge system of the application machine is a function of (a) the height of discharge and turbulent wake of the aircraft (b) the rate of material being discharged as active chemical, (c) the size range of the spray drop being released, (d) the intensity of the crosswind velocity component, (e) and the structure of the air in motion, turbulent or laminar as well as air stability as indicated by the presence or absence of temperature inversion, and height of the inversion above the treated crop. As can be seen, the local atmospheric conditions govern the rapidity of the pesticide cloud dispersal by diffusion and transport after release of the spray (or dry materials as well) from the application machine (Yates 1978).

The Agricultural Engineering Department at Davis has conducted many field drift tests and evaluated downwind movement and deposit by means of Mylar plastic fallout sheets, (15 × 46 cm), laid out at 6 to 8 stations in a logarithmic downwind pattern to a distance of 800 or 1000 m. High volume air samplers (0.68 m^3/min) were also placed at 3 to 4 of these downwind locations. Several passes of the aircraft or ground machine sprayer were made on a single swath line which enables us to (a) obtain sufficient sample strength to detect residues and air samples out to the distance chosen and (b) to release a quantity of material comparable to an application to 5 or 10 ha and (c) enable us to construct by computer regression analysis a pattern of downwind transport and deposit and (d) enable re-construction of the downwind multiple swath as a typical treatment might entail (Yates 1974).

Test runs were made with various atomizers for different drop sizes; with different formulations having viscosity, surface tension and evaporation characteristics with different ground and aircraft machines; and under a variety of local weather conditions of varying stability and wind velocities. Some of the data from these tests are shown in the following figures.

Fig. 9 shows the typical deposit pattern in the aircraft swath and downwind in the extended swath to 50 m. Fig. 10 indicates, first, the relationship of the flagged swath or step interval of the aircraft pattern, 2nd, the displaced or extended pattern which in reality is a part of the application and 3rd, the airborne or drift pattern which shows the long distance potential for drift loss from aerial spraying. It should be important for applicators and regulatory officials to recognize that the flagged swath is but a part of the pattern laid down by the aircraft and the displaced swath should not be termed drift. Drop size is probably the most important single function to affect application and drift.

Fig. 11 indicates drop size plots for various formulations, nozzles and nozzle sizes, pressures and rotary rpm for a number of different pesticide application systems. Largest size of 7000 μm vmd is shown for a wettable polymer marketed as Norbak®. Other hydraulic pressure nozzles are shown and a rotary type (MS) which produced around 100 μm vmd as does the 80005 fan nozzle. Drops of around 25 μm vmd were obtained with a two fluid (air and liquid under pressure) nozzle.

Fig. 12 indicates various drift test regression graphs for ground fallout or deposited residue of pesticide formulations released downwind by various aircraft applications. The topmost curve is for a D6-45 nozzle 90° to the airstream for drop size of around 300 μm vmd. The next two curves down are for a D6-46 nozzle 0°, 450 μm vmd with and without a polymer NT. It is to be noted that the polymer didn't alter the drift pattern significantly, in this case the salt formulation herbicide apparently neutralized the polymer. Next down is a run made with the then popular foam nozzles, followed by a run with D6 jets with and without the polymer. Again, no difference in drift is to be observed with use of the polymer and foam. The curve next to last is for a pulsed jet device which appeared to reduce numbers of small drops as well as the last curve for the Microfoil on the helicopter which showed least downwind drift (Akesson 1981).

Figs. 13 and 14 are for another series of field test drift runs, Fig. 13 is for ground fallout and Fig. 14 for airborne samples caught in glass fiber filters. As is to be seen a ground machine air carrier orchard sprayer gave highest drift loss as measured in both fallout and airborne. An 8003 fan nozzle on a fixed wing aircraft at 200 μm vmd gave next highest results. Curves 3 and 4 are for a helicopter with D4 jets 90° to the airstream with and without a polymer. Here the polymer appears to affect the fallout beyond about 250 m while the airborne shows a definite reduction in drift with use of the polymer. The fixed wing run with jet nozzles shows no difference in fallout and a reduction in airborne beyond 400 m. A ground rig with 8003 fan nozzles with and without polymer indicates a small reduction in fallout, but no reduction is shown in the airborne drift. The next to bottom curve is for a helicopter run with the Microfoil, and the last is a ground run with a low pressure (30 kPa) fan nozzle.

Fig. 15 presents a series of graphs showing summation of downward fallout for aircraft spraying with various drop size regimes. To obtain this data Mylar sheets (15 × 46 cm) were placed at 0.3 m intervals across the aircraft spray flagged swath. Mylars were placed on 1.5 m spacing out to 30 m and from these the drift station Mylars were added to the accumulated spray deposit to obtain the recoveries shown. As would be expected the Microfoil large drop size narrow drop range system deposited most of the spray in the first 10 m with but a few % out to the measured distance of 200 m, with close to 99% of the spray deposit total accounted for by 50 m distance. The D6 jet nozzles with 700 to 1100 μm vmd spray range gave a 96.0% recovery in the 50 m distance. The D6-46 (450 μm vmd) followed with 94% at 50 m and 97.2 out 200 m. Going to smaller drop size sprays such as 8003 fan nozzles at 200 μm vmd it is shown that 83% of the spray is accounted for at 50 m and 90.3 at 200 m. A Micronair run was made with 120-150 μm vmd sprays and shows a 51% recovery at 50 m and 59% at 200 m. Thus, again the larger drops, although admittedly biologically inefficient, can be largely confined to the treatment area of flagged and extended swath or out to 200 m downwind.

Overall the results indicate that large drop size sprays applied under similar weather conditions can affect significantly the downwind movement of applications whether by aircraft or ground. But, it is also to be noted that if the small drop size end of the spray distribution could be eliminated, such as the Microfoil system approaches, significantly smaller drop size sprays (vmd) could be used with greatly reduced drift loss (Yates 1985).

We conducted several large scale drift tests in mountainous terrain in Montana (1977) and New Mexico (1978b). Yates (1978) reported on the results of monitoring downwind fallout and airborne drift from applications of 300 to 500 ha in these areas. Applications were made with helicopters, Dylox at 4.68 ℓ/ha was applied to a plot (Fig. 16) in Montana and the graphs indicate the μg fallout and airborne out to about 4 km. These were sprays of around 250-300 μm vmd and the drift loss was notable in that it followed the valleys that led out of the spray area. Fig. 17 shows a drift plot pattern of Sevin application in New Mexico. Application constants were similar and a downslope wind (early morning) carried the spray for a measured distance of about 7 km down a valley floor which contributed to the high drift loss observed.

Monitoring for downwind fallout and airborne herbicide was done on two blocks of mixed brush areas on the N.W. California Coast. Block I consisted of about 50 ha located on the east slope of a valley running more or less north and south. The morning downslope winds carried the spray drift north so we set out 6 sampling stations with Mylar fallout sheets and 4 air sampling stations in a downwind pattern as shown in Table I. The closest station (1) was just inside the spray area, but wasn't sprayed, station (2) actually was sprayed while (3) was about 3 m outside the spray area. Station 4 was across the valley 550 m downwind, station (5) about the same distance further east and station (6) was on a hill at about 760 m distance from the closest spray.

TABLE I: Spray Block I Sprayed in 11:30 a.m. to 12:05 p.m.

Station	Location to Closest Spray	μg on Mylar	Air Filters
1	Inside area, not sprayed	277	
2	Sprayed, on edge of area	49, 220	
3	Outside edge spray area	35.6	19.4
4	550 m across valley, downwind	42.1	29.4
5	550 m near river, downwind	28.1	trace
6	760 m on hill above river, downwind	21.3	2.1
	Spray Block II Sprayed 1:50 p.m. to 3:15 p.m.		
1	Outside area, not sprayed	93.9	97.1
2	Edge of sprayed area but not sprayed	106.5	63.5
3	330 m south on road, downwind	52.7	70.9
4	336 m further south, downwind	63.5	59.4

In the afternoon the wind changed 180° and we placed our four stations south of block II an area of about 44 ha. Here, the stations were shown as in Table I at (1) next to spray area, but not sprayed, (2) close to sprayed edge of block, (3) 330 m south and (4) 365 m south of closest spray.

The application was made with 2,4-D Esteron, an amine formulation, at 4.5 kg acid ai per ha in a total of 112-115 ℓ/ha. A Hiller 12-E piston powered helicopter was used with 36 D8 jets direct at 0° to the airstream. A polymer was added to the spray mix, flight speed was about 100 km/h, drops size was estimated at 1500-2000 μm vmd. Table I indicates the residues found on Mylar and air filters which show significant amounts for both tests out to the furthermost stations of 760 m for Test I with a level of 2.1 total μg and 365 m for Test II with a level of 63.5 μg found. From this it is to be noted that even with a large drop size producing system, small but significant drift residues can be found especially in a valley situation where winds follow the valley contours and move drainage air for significant distances with little diffusion of the spray cloud.

SUMMARY

While biologists clearly have shown that drops of 100 to 200 μm dia. (at 1 to 1.5 drops/cm^2) are most effective for control of brush and other plant species, the problem of loss of small drops, generated by all of the presently available aircraft systems, which move out of the spray area as airborne drift, must be given priority consideration in any forestry herbicide spray work. This means that minimally the drop size vmd should be above 400-500 μm vmd and where any nearby sensitive crops, gardens or waterways exist even larger drops would be advisable. The application with giant size drops, over 1 mm dia., is partially offset by increasing total volume applied in order to maintain drop frequency necessary for effective coverage. This starts at 90 to 100 ℓ/ha and may require double this amount for very heavy growth situations.

The future of all spray activity rests to a great extent with development of more sophisticated, and likely to be expensive monodisperse spray application systems. Such devices for aircraft have been demonstrated experimentally but have not attracted development funding to make them a reality. Granular herbicides are only effective through the soil and do not hold very much promise for future use, although, several chemical companies continue to look at these as no-drift application. The increasing evidence of minimal or no health effects of the phenoxy herbicides including 2,4,5-T, might hopefully permit use of these valuable materials by the Forest Service (Gough 1987). No other family of herbicides has shown the capability for low cost brush control, and restoring these to forest lands use could see a turning point in maintenance of healthy and productive timber.

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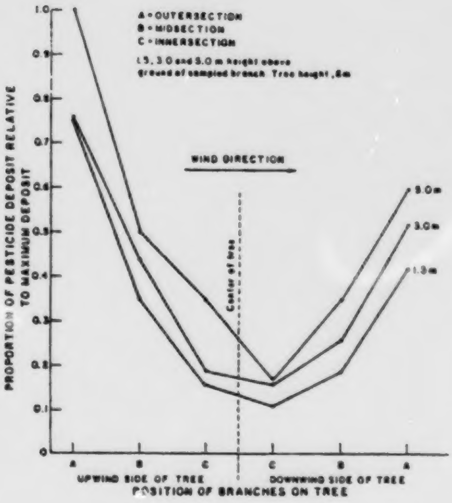


FIGURE 1: SPRAY DEPOSITION

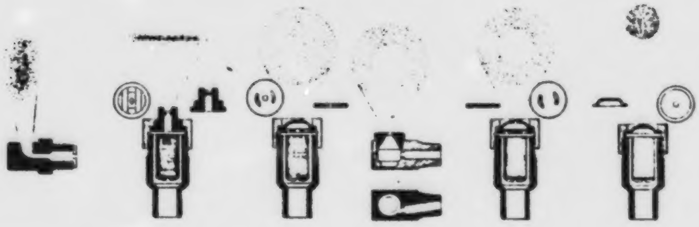


FIGURE 2: HYDRAULIC PRESSURE NOZZLES

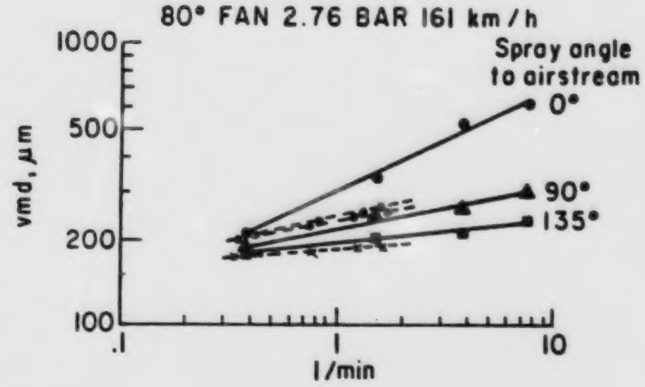


FIGURE 3: DROP SIZES FAN NOZZLES

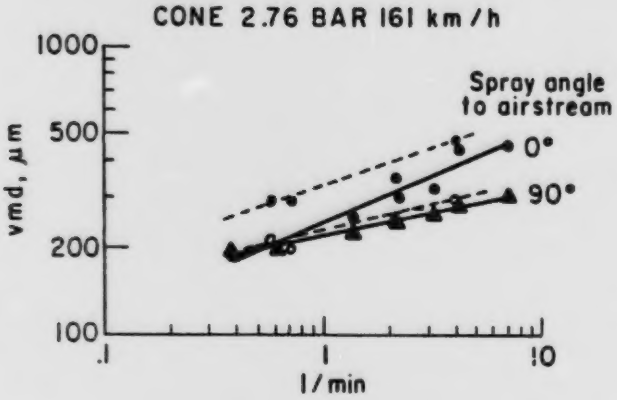


FIGURE 4: DROP SIZE CONE NOZZLE

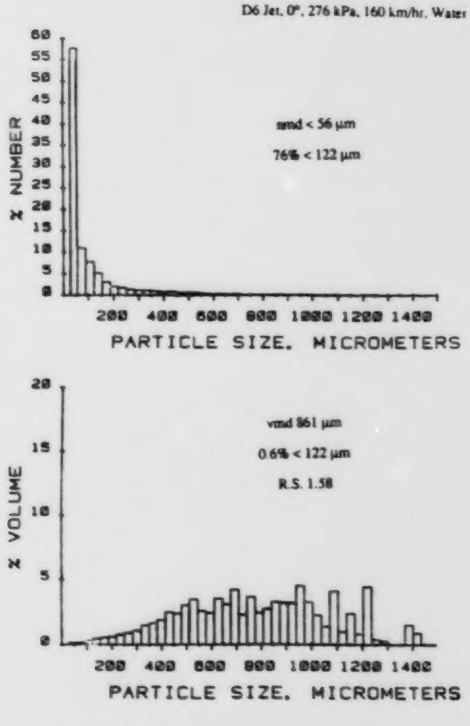


FIGURE 5: DROP SIZE JET NOZZLE

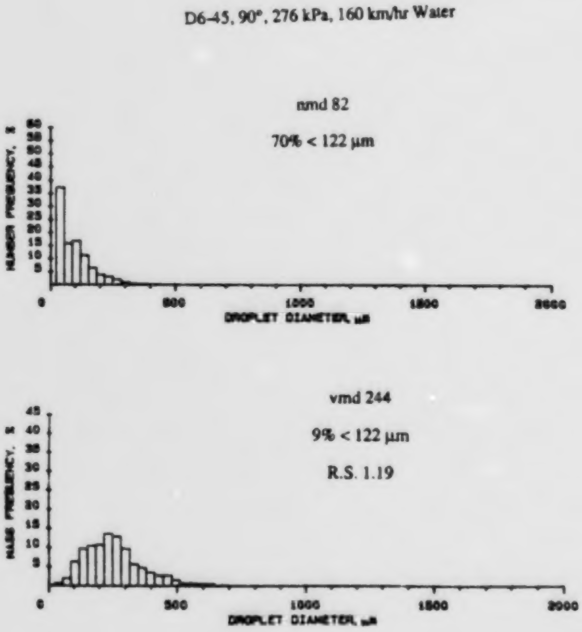


FIGURE 6: DROP SIZE HOLLOW CONE NOZZLE

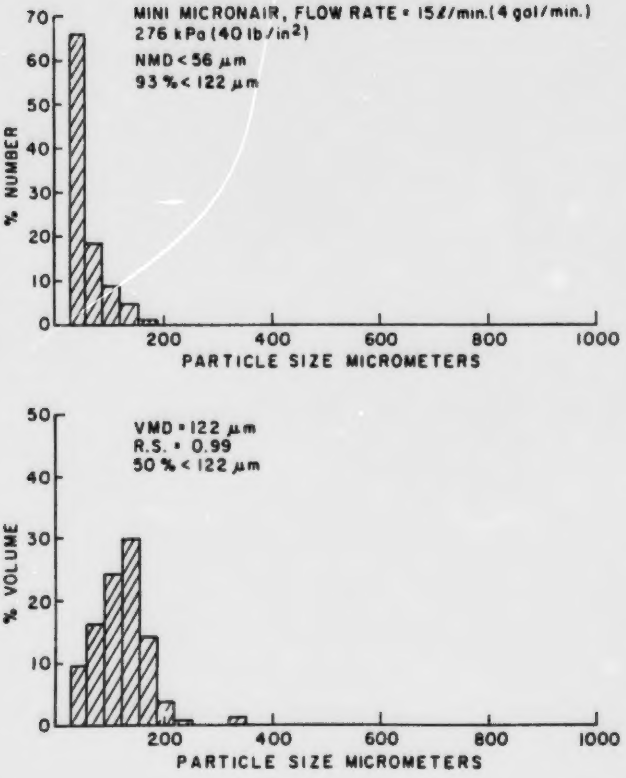


FIGURE 7: DROP SIZE ROTARY ATOMIZER

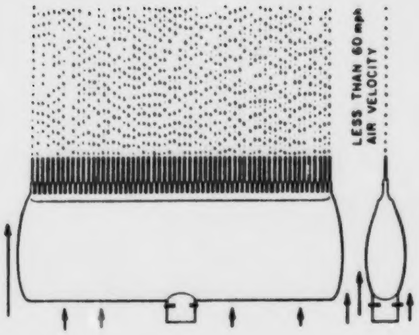

LESS THAN 60 mph
AIR VELOCITY

FIGURE 8: MICROFOIL ATOMIZER

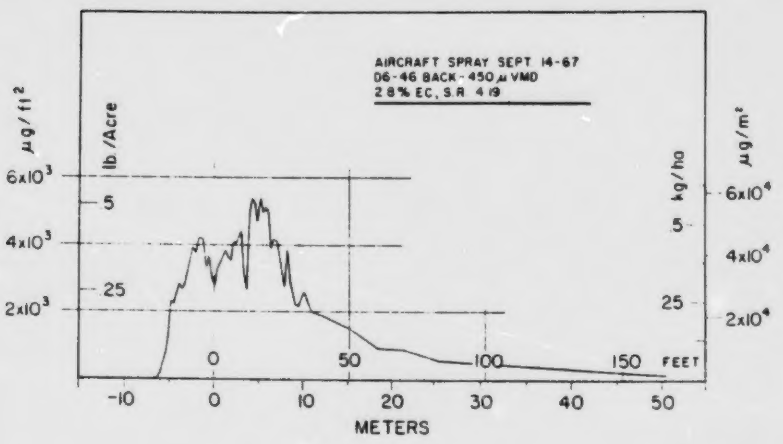


FIGURE 9: AIRCRAFT SPRAY PATTERN

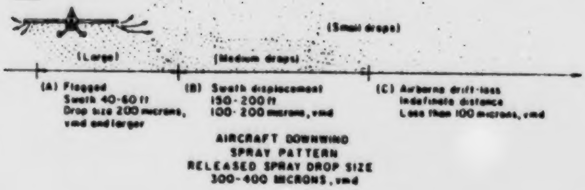

Wind 3-5 mi/hr
(Small drops)
(Large)
(Medium drops)
(A) Flagged
Swath 40-60 ft
Drop size 200 microns, vmd and larger
(B) Swath displacement
150-200 ft
100-200 microns, vmd
(C) Airborne drift-loss
indefinite distance
Less than 100 microns, vmd
AIRCRAFT DOWNWIND
SPRAY PATTERN
RELEASED SPRAY DROP SIZE
300-400 MICRONS, vmd

FIGURE 10: AIRCRAFT SWATH AND DRIFT PATTERN

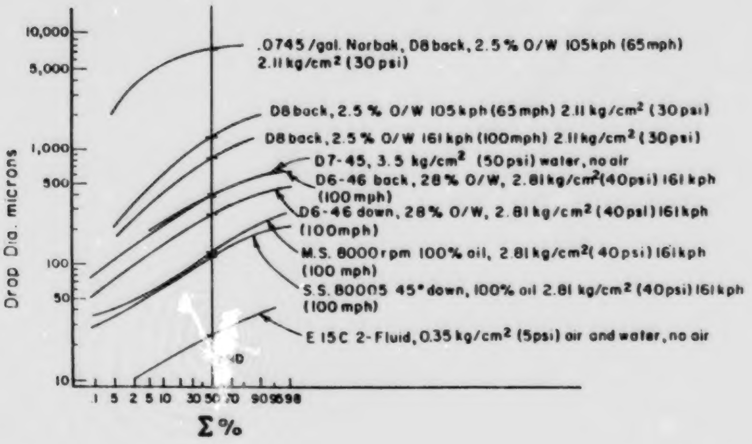
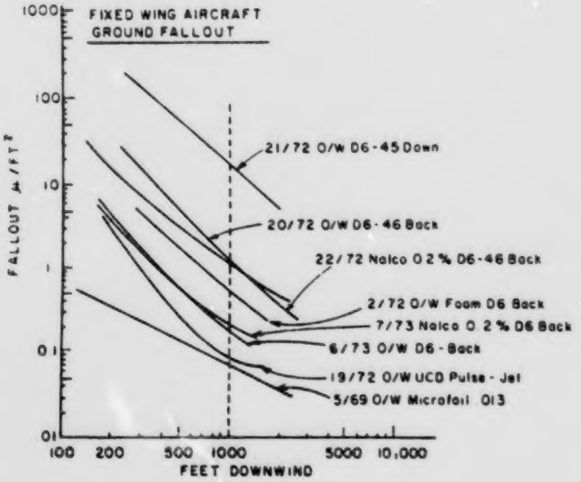


FIGURE 11: DROP SIZE SPECTRA VARIOUS ATOMIZERS



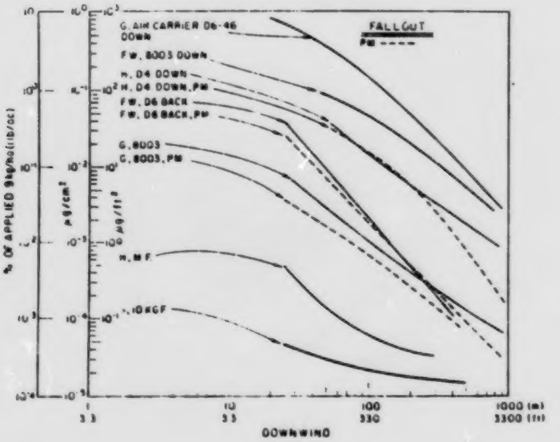


FIGURE 12: SPRAY FALLOUT VARIOUS ATOMIZERS

FIGURE 13: SPRAY FALLOUT VARIOUS ATOMIZERS

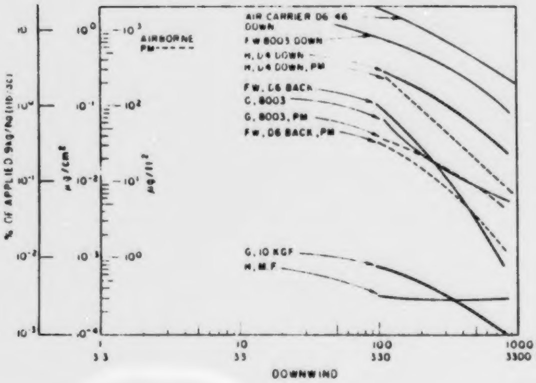


FIGURE 14: AIRBORNE SPRAY VARIOUS ATOMIZERS

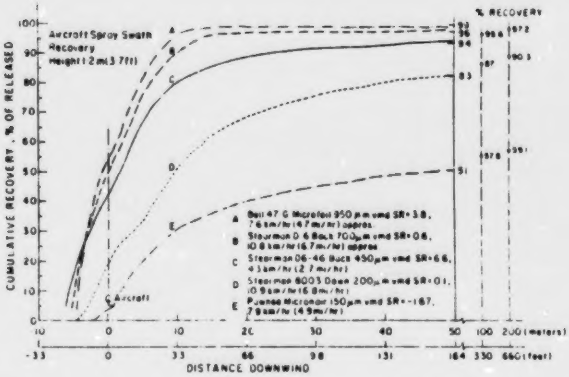


FIGURE 15: CUMULATIVE SPRAY DEPOSIT

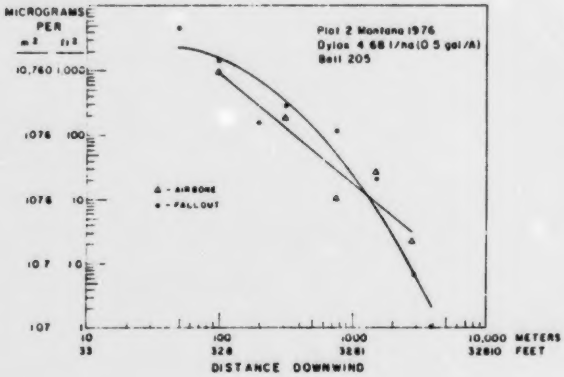


FIGURE 16: DRIFT PATTERN, MONTANA

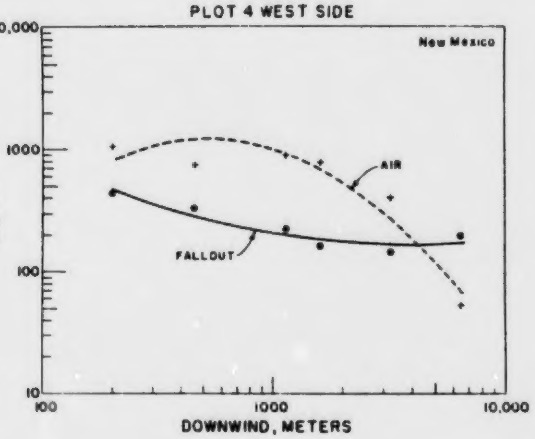


FIGURE 17: DRIFT PATTERN, NEW MEXICO

CANOPY PENETRATION AND DEPOSITION OF SMALL DROPLETS

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ABSTRACT — It is desirable to improve forestry pesticide applications in terms of efficacy achieved per kilogram of active ingredient applied, environmental impact caused, and resources expended. The distribution of pesticide deposit resulting from a spray application is an important consideration for all these concerns. In general the proportion of active ingredient deposited on-target during pesticide applications should be maximized. This in turn minimizes off-target deposit, and hence reduces environmental impact, active ingredient wasted and application costs.

A discussion is made of the physical processes involved in canopy penetration and deposition of small droplets, and the influence of physical variables such as atmospheric boundary-layer stability, windspeed and turbulence. In addition a review is made of selected publications concerning pesticide distribution from forestry spray applications made using small droplets, and different aspects of deposit distribution are discussed.

RÉSUMÉ — Il est souhaitable d'améliorer l'efficacité des épandages de pesticides en forêt en ce qui a trait aux résultats obtenus par kilogramme d'ingrédient actif épandu, à l'impact sur l'environnement et aux ressources dépensées. Voilà pourquoi il est important de tenir compte de la distribution des retombées de pesticides qui suivent l'épandage d'un aérosol. En général, il faudrait maximiser les proportions d'ingrédient actif retombant sur la cible pendant l'épandage d'un pesticide. Les retombées à l'extérieur de la cible seraient ainsi réduites au minimum, d'où une réduction des répercussions sur l'environnement, des pertes d'ingrédient actif et des coûts d'épandage.

La discussion porte sur les processus physiques contribuant à la retombée des petites gouttelettes et à leur pénétration dans le couvert forestier ainsi que sur l'effet de variables physiques comme la stabilité des couches atmosphériques frontières, la vitesse du vent et la turbulence. On fait aussi une revue de publications choisies portant sur la distribution des pesticides à la suite de l'épandage d'aérosols à gouttelettes petites en forêt et l'on traite de divers aspects de la distribution des retombées.

INTRODUCTION

The penetration and deposition of droplets in a forest canopy is an important step in the aerial application of pesticides affecting both the efficacy and environmental impact obtained from an application through its effect on the proportions of on and off-target deposit. The fate of a droplet is strongly influenced by its size. This paper deals with small droplets, which are taken to be those with a diameter of less than 100 micrometres. The physical significance of this size limit flows from the sedimentation velocity of a droplet of this size, which is about 0.25 m/s. This sedimentation velocity is usually less than the vertical windspeeds found in the atmospheric boundary layer, and therefore the dispersal of droplets with diameters less than 100 micrometres is greatly affected by the prevailing meteorological conditions.

CANOPY PENETRATION

Canopy penetration by small droplets occurs by turbulent diffusion or sedimentation (Chamberlain 1975). Once inside the canopy droplet advection, i.e. downwind transport of the droplet assists in canopy penetration. Turbulent diffusion is the dispersal of droplets by atmospheric turbulence (Pasquill 1974). The relative importance of these processes depends on the strength of turbulence in the forest canopy. This in turn is determined by the prevailing meteorological conditions, in particular the atmospheric stability and geostrophic windspeed, i.e. windspeed arising from the atmospheric pressure gradient and the earth's rotation (Smith et al. 1972, Sutton 1953).

The sedimentation velocities of 50 and 30 micrometre diameter droplets are about 0.07 and 0.025 m/s respectively. In a forest canopy the standard deviation of vertical windspeed can often reach 0.5 m/s (Grant et al. 1986). By comparing these figures it can be seen that canopy penetration by droplet sedimentation, i.e. the droplet falling under its own weight can be considerably augmented by turbulent diffusion. The variables that affect spray droplet penetration into the forest canopy by turbulent diffusion include those that affect spray cloud dispersal above the canopy plus some canopy-related variables. The first category includes atmospheric boundary layer stability, and the windspeed and air temperature profiles. These variables exert their influence by changing the strength of turbulence and hence the rate of turbulent diffusion through the canopy. Turbulent diffusion of droplets in the atmosphere is usually defined using the concept of eddy diffusivity (K) (Pasquill 1974). This variable is used to quantify the diffusing power of the atmosphere resulting from the presence of turbulence, and it increases with the amount of turbulence present. A height profile of eddy diffusivity inside a deciduous canopy is shown in Figure 1 (Rauner 1976), from which it can be seen that eddy diffusivity increases with height. This general trend is apparent in many plant canopies, and results from the damping of turbulence by the canopy. The strength of turbulence in the canopy is governed by atmospheric boundary layer stability (Thom 1975). In stable conditions, where temperature increases with height, turbulence is damped by the temperature gradient and turbulent diffusion is weak, and windspeeds inside the canopy are relatively low. These conditions are often found in early morning or late evening. In unstable conditions, where temperature decreases with height, turbulence is enhanced by the temperature gradient, and turbulent diffusion is strong, and windspeeds inside the canopy are relatively high. These conditions are generally found in the middle part of the day.

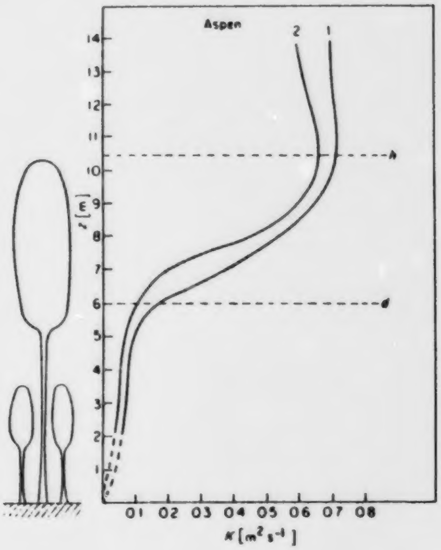

FIGURE 1: VERTICAL PROFILE OF EDDY DIFFUSIVITY K IN AN ASPEN CANOPY (RAUNER 1976).

Aircraft vortices also affect canopy penetration by changing the structure of turbulence, although the extent of their influence is dependent on the vortex strength, cloud release height and the state of the boundary layer between release height and canopy top. Penetration is also affected by the dropsize spectrum of the spray cloud on reaching the canopy, which in turn is influenced by the tank mix volatility, air temperature profile, and for water-based sprays the relative humidity. The efficiency of inertial impaction increases with dropsize (May and Clifford 1967). Thus for droplets with diameters of less than 100 micrometres canopy penetration improves as dropsize is reduced, i.e. droplets infiltrate the canopy more effectively as dropsize is reduced.

The canopy-related variables that affect penetration include plant height and density, and leaf size and foliage density. These canopy-related variables affect canopy penetration in two ways, through the size and number of the obstacles on which droplets may be deposited, and by modifying the wind profile in the canopy. As canopy density increases windspeeds and turbulence inside the canopy are reduced, and turbulent diffusion is weakened. Canopy penetration and drop deposition are inter-related in that if drop deposition is very efficient, canopy penetration will be lessened. Conversely if drop deposition is not efficient drops remain airborne for longer and canopy penetration is increased.

DROPLET DEPOSITION

Droplet deposition on the forest canopy occurs mainly by inertial impaction and sedimentation, although electrostatic attraction between droplet and canopy may also contribute to deposition. Inertial impaction is the type of deposition that occurs when an airborne drop approaches an obstacle in the airflow; the airflow divides and flows around the obstacle, whereas the drop continues under its own momentum to collide with the obstacle.

The droplet impaction efficiency, i.e. the proportion of drops approaching the obstacle that are deposited, is principally determined the windspeed, dropsize and obstacle size (Chamberlain 1975). Inertial impaction efficiencies for droplets have been measured by May and Clifford (1967) for objects of various shapes, including cylinders, spheres, ribbons and discs, for droplet diameters of 20, 30 and 40 micrometres, in windspeeds ranging from about 2 to 6 m/s. Figure 2 shows impaction efficiencies measured for a cylinder, to which a single conifer needle is a good approximation. Impaction efficiency E is plotted against impaction parameter P. The latter is calculated by dividing the stop distance of the droplet by the width or diameter of the obstacle. The stop distance of a drop is the distance it would travel horizontally in still air before being brought to rest by air friction, and depends on the velocity of projection and droplet diameter. Figure 3 shows stop distances for various dropsizes at various velocities of projection.

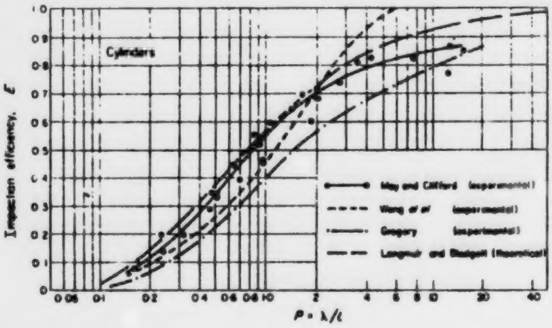

FIGURE 2: EXPERIMENTAL AND THEORETICAL IMPACTION EFFICIENCY OF CIRCULAR CYLINDERS (MAY AND CLIFFORD 1967).

Measured impaction efficiencies for a cylinder varied from less than 10% for an impaction parameter of about 0.2, to about 85% for an impaction parameter of about 10. In practical terms, if the cylindrical obstacle was 1 millimetre in diameter, similar to a conifer needle, and the windspeed was 1 m/s, droplets with diameters of 8 and 60 micrometres would have impaction efficiencies of about 8 and 85% respectively. If the windspeed was 3 m/s, droplets with diameters of 5 and 40 micrometres would be required to give similar impaction efficiencies.

The efficiency of inertial impaction of drops inside a forest varies with height due to changes in windspeed. In general the average windspeed increases with height above ground level (Oliver 1971). Figure 4 gives an example of the average windspeed profile (u) inside a sitka spruce canopy about 10.5 m in height (Jarvis et al. 1976). It is apparent that windspeed increases markedly in the top one third of the canopy, while windspeed in the lower two-thirds is roughly constant, and low. For comparison the distribution of foliage with height is also shown (L, Leaf area index, $m^2 m^{-2}$). The average windspeed is well attenuated at the height of maximum foliage density, about 7 m.

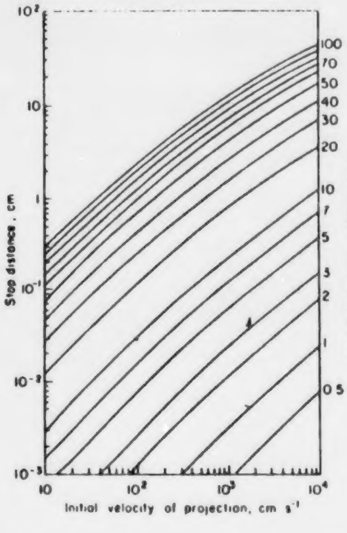

FIGURE 3: STOP DISTANCE OF UNIT DENSITY SPHERES (CHAMBERLAIN 1975).

Inertial impaction efficiency is also affected by the structure of the airflow around the branch. The structure of airflow around a spruce twig has been investigated by Grant (1983), who found that at windspeeds of less than about 1.5 m/s (3 mph) the airflow penetrates well between the needles and hence they will act as individual collectors. However in windspeeds above about 1.5 m/s the structure of the airflow changes, and rather than passing between the needles most of the air now passes around the cylinder formed by the needles on the twig. The implication this has for impaction efficiencies is that at low windspeeds the width of a filter element (needle) is about 0.15 cm, whereas in high windspeeds the filter element is, roughly speaking, the twig which has a diameter of about 1.5 cm, ten times greater. Thus the increase in impaction efficiency resulting from increased windspeed is not as great as would be expected from consideration of windspeed alone.

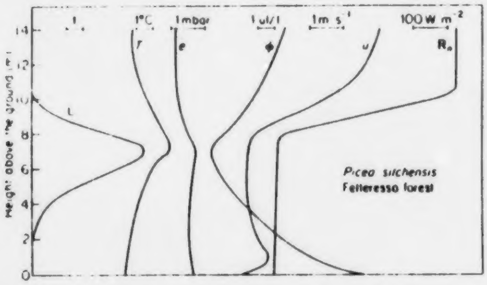

FIGURE 4: EXAMPLES OF MEAN HOURLY PROFILES OF MICROMETEOROLOGICAL PROPERTIES IN A SITKA SPRUCE CANOPY (JARVIS ET AL. 1976).

Droplet deposition by sedimentation is the settling of a drop under its own weight, onto an obstacle. The sedimentation or terminal velocity of a droplet is dependent on dropsize (Fig. 5). Both inertial impaction and sedimentation are at work in depositing spray drops on a forest canopy, however as with penetration their relative importance depends on the prevailing meteorological conditions and the dropsize spectrum of the spray cloud.

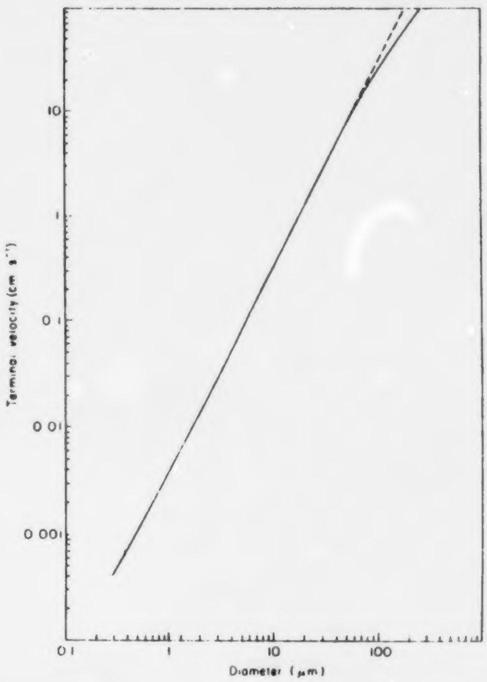

FIGURE 5: SEDIMENTATION VELOCITIES OF UNIT-DENSITY SPHERES (CHAMBERLAIN 1975).

EXPERIMENTAL INVESTIGATIONS

Three published investigations have been chosen to illustrate various aspects of small droplet dispersal in a coniferous forest canopy. The first of these was carried out by Armstrong and Yule (1978). The spray application was designed to imitate an ultra-low volume (ULV) application of the insecticide fenitrothion which has been widely used in eastern Canadian forests to control spruce budworm populations at the larval stage. A dyed solution of the tracer Tris (2-ethyl hexyl) phosphate (TOF) in the oil Arotex 3470 was applied at about 390 g/ha (TOF) in a total volume application rate of about 1.1 L/ha. The spray application was made using a Cessna 185 equipped with Micronaire AU 3000 atomizers set to provide the maximum recommended rotation rate. The aircraft flew at about 19 m above canopy top at an airspeed of about 45 m/s (100 mph). The area sprayed was covered with white spruce trees with an average height of about 6 m (20 ft.). Meteorological measurements were made on-site at 15 m above ground level (agl). The spray was applied in a very stable boundary layer when the measured average windspeed was about 0.5 m/s (1 mph), from the south. Foliage samples were taken from three sample trees in four different height zones, 0–1.5, 1.5–3, 3–5 and 5–6 m agl, from four different aspects, NE, SE, SW and NW. Vegetation surrounding the sample trees was cleared away. Tris (2-ethyl hexyl) phosphate deposited on foliage samples up to 100 g in weight was extracted and quantified by gas chromatography. Kromekote cards (0.1 × 0.1 m) were placed adjacent to the tree in each height band at each aspect and on the ground. Glass plates were also placed on the ground to collect spray for colorimetric measurement. The dye in the tank mix enabled dropsize spectra on the cards to be estimated from stain diameter measurements. From these measurements the number and volume median diameters were estimated to be 56 and 88 micrometres respectively. These values probably overestimate the values for the foliar deposits, due to the size of the cards compared to spruce buds and needles. The small needle size enhances inertial impaction and hence median diameters would be smaller than on the cards. The meteorological conditions during this spray application represent an extreme in terms of the low windspeed and very stable boundary-layer, both of which imply that turbulence in and above the canopy was very weak. The importance of turbulent diffusion in canopy penetration was minimized due to the weak turbulence present. Similarly the light winds would have minimized the importance of inertial impaction as a deposition process.

Vertical deposit variation

The measurements of foliar deposit from Armstrong and Yule's investigation illustrate several features of small droplet deposit patterns in a coniferous canopy. The vertical deposit variation has been assessed by calculating average TOF deposits for each height zone, using the published measurements from all aspects and trees (Table 1). Although the differences between deposits measured in adjacent height zones are not statistically significant (t-test) there is a clear trend showing that deposit increases with height above ground. In the top height zone the TOF deposit is about 38% higher than in the lowest height zone. The increase in spray deposit with height arises from two causes. First, windspeed increases with height in the canopy, this implies that drop impaction efficiencies on foliage will increase with height, i.e. needles in the upper part of the canopy will be more efficient collectors than those at the bottom of the canopy. Secondly, the canopy acts as a filter with dropladen air entering from above. Thus airborne drop concentrations will also, on average, increase with height. This implies that at the bottom of the canopy fewer drops are available for deposition than at the top of the canopy. Both of these factors cause an increase in drop deposit with height agl.

In this investigation the canopy around the sample trees was deliberately opened up by cutting vegetation. This would have had the effect of increasing windspeed and airborne droplet concentrations around the bottom part of the sample trees, both of which will increase spray deposit near the bottom of the tree in comparison with the unaltered canopy. It is likely that the difference in deposit at the top and bottom of the canopy would have been more pronounced had the openings not been made. The reported results imply that greater vertical variation can be found in natural canopies.

Another feature of the vertical distribution of small drop deposit in a coniferous canopy reported by Armstrong and Yule was the difference in deposit on needles on the upper and lower surfaces of branch tips. Measured average TOF deposits were 26.1 and 17.8 ppm respectively on foliage from the upper and lower 180 degree portion of selected branch tips, i.e. deposit on the upper portion was about 50% higher than that on the lower portion. The difference in deposit found on the upper and lower surfaces of branch tips arises partly from the fact that deposition by sedimentation occurs from above onto the upper surface of an obstacle. However turbulent diffusion will also reinforce this bias because the cloud is diffusing down from above, i.e. on average air parcels moving past the branch from above contain higher drop concentrations than those from below.

TABLE 1: Measurements of TOF deposits on foliage (based on Armstrong and Yule 1978)

Height Zone	Average deposit (ppm)	S.D.	S.E.
Vertical variation			
0-1.5 m	4.5	3.0	0.9(n=12)
1.5-3 m	5.7	5.7	1.6
3-5 m	5.9	4.0	1.2
5-6 m	6.2	3.7	1.1
Variation by aspect			
Upwind aspects (SE & SW)	6.7	4.9	1.0(n=24)
Downwind aspects (NE & NW)	4.4	2.8	0.57
Radial variation			
Inner 1/3	1.4	0.91	0.15(n=36)
Middle 1/3	2.5	1.6	0.27
Outer 1/3	4.8	3.4	0.56

Average TOF deposit measured on glass plates at ground level in the treatment area was about 250 g/ha, nearly 68% of the emitted rate of about 370 g/ha.

Deposit variation by aspect

To compare the variation of foliar deposit by aspect the TOF measurements from the two upwind and the two downwind aspects have been averaged over all heights and trees (Table 1). The average deposit on foliage from upwind aspects was significantly higher than that on foliage from downwind aspects (t-test, 5% level). The higher deposit on the upwind side of the tree may be partly explained by the fact that as the cloud moves downwind the upwind foliage will be intercepted first. Thus on average, airborne drop concentrations on the upwind side of the tree will be greater than on the downwind side. In addition the upwind side of the tree will experience higher windspeeds and thus drops will have greater impaction efficiencies than on the downwind side.

Radial deposit variation

Another feature of the distribution of small droplet deposit on coniferous canopies is the horizontal variation in a tree. This was examined by Armstrong and Yule by measuring the TOF deposit on foliage at different lateral positions on whole branches collected at three heights, 1.5, 3, and 5 m agl. They dubbed the horizontal variation within a tree as radial variation. Their measurements are also summarized in Table 1. Deposits were averaged over all aspects, heights and trees. The measured average deposits were significantly different on foliage taken from the inner, middle and outer one third of the white spruce branches (t-test, at 0.1% level), with a corresponding ratio of about 1.2:4, i.e. deposit on foliage on the outer one third of the branch was about four times that on foliage taken from the inner one third. The radial variation in deposit results from different exposure of the foliage at different positions along the branch, with foliage being progressively more sheltered the closer it is to the trunk. Away from the branch tip drop deposition by sedimentation is reduced because the foliage is sheltered by that above. Drop deposition by inertial impaction also decreases away from the branch tip because turbulent diffusion is damped by the sheltering foliage, and reduced windspeeds reduce inertial impaction efficiency.

Deposit variability

Variability is another important feature of deposit distribution demonstrated by Armstrong and Yule's measurements. The standard deviation in measured TOF deposits expressed as a percentage of the respective average varied between about 60 and 100% (Table 1). The foliage samples from which TOF was extracted and quantified weighed up to 100 g, an amount which comprises thousands of needles. It is apparent that the variability in foliar deposit is large.

The second investigation to be reviewed is that by Joyce et al. (1981). The spray application was designed to control larval populations of Pine beauty moth in Lodgepole pine plantations in Scotland. A solution of the insecticide fenitrothion in a low volatility organic solvent was applied at 75 g/ha (active ingredient) in a total volume of 0.5 L/ha. Fluorescent particles (FP's) were added to the tank mix for use in quantifying spray deposit. Two similar applications were made over the same area, two days apart, using a Pilatus Porter aircraft equipped with Micronair AU 3000 atomizers set to provide the maximum recommended rotation rate. The aircraft flew at about 12 m above canopy top at an airspeed of about 50 m/s (110 mph). From previous measurements made using a laser spectrometer in a wind tunnel, the number and volume median diameters at emission were estimated to be about 24 and 77 micrometres. From the FP mixing ratio achieved Joyce et al. estimate that 90% or more of the spray volume was marked, however by number less than 50% of the spray drops were visible. The area sprayed was covered with a Lodgepole pine plantation with an average tree height of about 5.5 m (18 ft). Meteorological measurements were made on-site at 9 m agl. During Spray 1 the wind was light, about 2.5 m/s (6 mph) and the boundary-layer was unstable, whereas during Spray 2 the wind was strong, about 7.5 m/s (17 mph) and boundary layer stability was near-neutral. After the spray branch tips were removed from ten trees, at two heights, 2 and 5 m agl., and from four aspects, N, S, E and W. Ten needles were examined from each of the 80 branch tips and the total number of stains containing FP's was recorded on each needle. In addition the number of stains with 25-39 and 40 or more FP's, was noted. Ground deposit was sampled by placing Bristol cards (0.05 × 0.05 m) horizontally at ground level. The total number of stains containing FP's was recorded on each card together with the number containing 10-19, 20-39 and 40 or more FP's. The meteorological conditions present during spray 2 represent an extreme in terms of the high windspeed, which will provide strong turbulent diffusion and efficient inertial impaction thereby minimizing the importance of sedimentation in canopy penetration and drop deposition.

Vertical variation in deposit

Table 2 summarizes the measurements made by Joyce et al. Foliar deposits were averaged over all trees and all aspects. Foliar deposit per unit area refers to total leaf surface area. The results show that measured spray deposit increased with height in the canopy. For spray 1 the foliar deposit at 5 m agl was about four times that at 2 m. For spray 2 this ratio was about 22. The greater vertical variation in spray 2 was partly due to the increased tree top deposits, about three times higher in windspeeds of 7.5 m/s at 9 m than in windspeeds of 2.5 m/s. This difference is partly due to higher inertial impaction efficiencies caused by the higher windspeed. The deposit measured on ground samplers was low at about 4 and 2% of the application rate in sprays 1 & 2 respectively.

TABLE 2: Fenitrothion deposits on needles and ground cards (from Joyce et al. 1981)

Height agl (m)	Deposit (ng/cm^2)	
	Spray 1	Spray 2
5	52	160
2	12	7.3
Ground	27.6	14.8

Deposit variation by aspect

From their measurements Joyce et al. could not find significant differences in deposit with aspect after spray 1, the light wind case. However, after spray 2 the tree top deposits were significantly (5 times) greater on the upwind side although at the tree bottoms deposits were again similar at each aspect.

Deposit variability

Joyce et al. also noted great variability in deposit from tree to tree. Some of this they were able to attribute to different exposure, with those trees in open parts of the canopy, e.g. adjacent to rides, receiving greater deposits.

An investigation into spray deposit patterns from small drop applications to a mixed forest canopy has been made by Sundaram et al. (in prep.). An aerial application of fenitrothion was made at 280 g/ha with a total volume application rate of 1.5 L/ha. The fenitrothion (15% v/v) was emulsified in dyed water (81% v/v water, 1% v/v Rhodamine B). The spray was applied using a Cessna 188 aircraft, equipped with Micronair AU3000's, flying at an airspeed of about 44 m/s (100 mph) at about 15 m above the canopy top. The area sprayed was covered with mixed forest, mainly balsam fir, cedar and white birch, with an average tree height of about 8 m. Meteorological measurements were made on-site at 5 m agl. During the spray the measured average windspeed was about 0.5 m/s (1 mph), the average air temperature was about 15°C and the relative humidity about 80%. The spray was applied in mid-June between 7 and 8 a.m. with little cloud cover. From the conditions described it is likely a stable boundary-layer was present. After the spray single branch tips 0.3 m long were removed from six balsam fir trees (average height 7 m) at 1, 3 and 5 m agl from four aspects. Foliage from the crown interior were also collected at 1 and 3 m agl. To sample ground deposit kromekote cards (0.1 × 0.1 m) and glass plates were placed horizontally at about 0.15 m above the forest floor. Fenitrothion residues in the foliage and on glass plates were quantified by gas chromatography, and dropsize spectra on the cards were estimated from stain measurements and stain factors. The number and volume median diameters measured on the Kromekote cards were about 36 and 58 micrometres respectively.

Vertical and radial variation of deposit

The measurements made by Sundaram et al. are summarized in Table 3. Fenitrothion deposit on the canopy increased with height above the ground, and at 5 m was about 72% higher than that at 1 m agl. Fenitrothion deposits measured on glass plates at ground level were equivalent to about 26% of the application rate. Foliar deposits also increased radially outward, with branch tip deposit 45 and 29% greater than interior deposit at 1 and 3 m agl respectively.

TABLE 3: Measurements of fenitrothion deposit on balsam fir foliage and ground plates (based on Sundaram et al.)

Vertical and radial variation of deposit

Height (m)	Fenitrothion deposit (ppm, SD in ( ) as %) Interior	Tip	(ng/cm²) Interior	Tip
5	—	5.0 (26)	—	75
3	2.8 (31)	3.6 (30)	41	54
1	2.0 (12)	2.9 (18)	30	43
Ground			730	

Deposit variability

Fenitrothion deposit on the foliage showed considerable variation. Measurements of fenitrothion were made using samples comprising all foliage from eight 0.3 m long branch tips, e.g. at each height one branch per aspect was pooled from two trees. After maceration and mixing 5 g portions of foliage were taken for fenitrothion extraction. The standard deviation in the three measurements of fenitrothion deposit at any one height averaged about 25%.

DISCUSSION

A significant feature of the spray deposit pattern observed in all the investigations reviewed is the increase in spray deposit with height above ground. This was apparent in spray applications made in meteorological conditions covering a range of windspeeds and atmospheric stabilities. Radial deposit variation is another significant feature observed in the results presented, with deposit increasing towards the branch tip. Both spray applications in which radial deposit variations were observed were carried out in a stable boundary-layer with light winds. It is possible that this variation would be reduced if turbulent diffusion were stronger. Great variability in spray deposit was also apparent in each investigation. This variability has implications for insect pest control because, were it able to be reduced, a.i. rates could also be reduced without causing foliage protection to become patchy. It is likely that deposit variability could be reduced by flying higher and in more turbulent conditions. Other aspects of observed deposit variation include the increase in deposit from the downwind to the upwind side of the tree, and from the bottom to the top of the branch.

In each of the investigations reviewed the spray applications showed some general similarities, e.g. canopy height 6-8 m, cloud release height 12-19 m above canopy, aircraft weight and flying speed, and dropsize spectra with VMD's 58-88 micrometres and NMD's 24-36 micrometres. However a wide range of meteorological conditions were present during the spray applications. A comparison has been made of measured foliar and ground deposits (Table 4) to demonstrate possible meteorological effects on spray deposit patterns. Foliar deposits on branch tips and ground samplers have been compared because these measurements were common to all investigations. Deposit measurements have been adjusted to a.i. application rates of 100 g/ha of TOF or fenitrothion, as appropriate. Deposit measurements expressed in ppm were converted to ng/cm² using the measurements of needle surface area per gram made on balsam fir needles by Sundaram et al. Although white spruce and balsam fir needles are slightly different in size this approximation is suitable for the comparison made.

TABLE 4: Comparison of foliar and ground deposit measurements reviewed (deposit per 100 g/ha applied)

Position on tree:	Peripheral Foliage (ng/cm²) Top	Bottom	Ground Samplers (ng/cm²)
Armstrong and Yule	25.4	17.9	676
Joyce et al. Spray 1	69.3	16.0	36.7
Spray 2	213	9.7	19.7
Sundaram et al.	26.8	15.4	261

From Table 4 it is apparent that measured spray deposit near the tree bottom is, approximately speaking, similar in all cases, despite the fact that these investigations covered a range of atmospheric stabilities, windspeeds and canopy densities. However measured spray deposit at tree top and on the ground were not in good agreement. High spray deposit near the tree top was found during those conditions when windspeed at the tree top was high (Joyce et al., spray 1 & 2), and low spray deposit was found when light winds and a stable boundary-layer resulted in low windspeeds at the tree top (Armstrong and Yule, Sundaram et al.). This comparison suggests that a greater proportion of the applied active ingredient is deposited on the canopy during neutral or unstable conditions with windspeeds greater than 2.5 m/s (5 mph) at 10 m agl. Spray deposit on ground samplers was also highest in those trials when windspeeds inside the canopy were low. This comparison suggests that ground contamination may be minimized by spraying in neutral or unstable conditions when windspeeds exceed 2.5 m/s (5 mph) at 10 m agl. However it should be noted that the difference between the ground deposit measurements may be partly caused by differences in canopy density, and the dropsize spectra (upper end).

The practical value of measurements of spray deposit patterns within the canopy is realized when they can be compared with pest distributions, and pesticide use strategies modified, e.g. by using different meteorological conditions, to better match the distribution of pest and pesticide. Measurements of these distributions are few and it appears there may be an opportunity to improve pesticide applications by gathering more information about them both.

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SESSION III DISCUSSION PERIOD

Panel Chairman — M. Pelletier
Panel Members — A.M. Drummond, C.S. Parkin, N.B. Akesson, N.J. Payne

Jules Picot:

I want to make a comment to Professor Akesson about drop spectra that you showed for the herbicide atomizers.

We have been doing some work for Dr. Payne and we used our light scattering probe and as with the work on the types of atomisers we have been using for insecticide work, droplet numbers increase as droplet size goes down even for low wind speeds. So that would tend to explain why you are getting drift of very fine particles across that valley and also, I guess, it is a bit different from your own experience and I am not sure if you used your light scattering probe for those spectra.

Norm Akesson:

I agree with your comment on droplet number and size.

Dan Cronin:

The question is for Dr. Drummond. The BC perspective has most aerial application being conducted by helicopter and I am wondering if you have any comparative comments on production of vortices, and perhaps, lateral deposition in relation to what you presented on fixed wing aircraft?

Al Drummond:

Before I give any technical statement, I would like to say that ACAFA, earlier this year, sponsored a workshop in Toronto on the aerial application of herbicides in forestry. One of the main points of discussion was the comparison between helicopter and fixed wing machines. Professor Akesson and myself were there to aid the discussions. The general perception of helicopters being more efficient, as I can remember from the discussion there, was one of perception rather than one of fact.

In fact, in the United States, the helicopter is viewed, in Western States, as the good guy and the airplane is viewed as the bad guy where in British Columbia it is the converse.

One thing that did come out of that meeting, which I agree with, is that the helicopter does have a much larger downwash only when it approaches the hover. When it is flying at an operational speed, perhaps above about 60 knots, it has a shed vortex system which is not unlike a low aspect ratio wing which is much stronger than a high aspect ratio wing but it exhibits a lot of the downwash, a lot of the stability characteristics of the vortex system shed by a normal high aspect ratio wing. It behaves more like a triangular wing would if it were flying.

Regarding lateral dispersion, I wouldn't really want to say anything about it. At the meeting a gentleman did say that they wanted the boom to remain inside the rotor dimension, and in that case, a lot of their drift was reduced.

Dave Maass:

One question keeps bothering me all along here. We have this phenomena on operations that we call drift and generally we mean the movement of small droplets moving off target. Speaker after speaker has pointed out the use of small droplets and the utility of small droplets with regards to efficacy, canopy penetration and such . . . I am addressing this question to any of you who would like to try to explain to me, a forester, who knows very little about droplet phenomena, how can we rationalize or how can we have both apparent phenomena (drift-efficacy). Are they mutually exclusive or are we talking about the same thing or are we talking of different phenomena altogether?

Norm Akesson:

Let me try first. It is a conundrum in many respects. . . . I don't know the answer but let me rationalize it this way.

The evidence that the small drops are more effective in actual biological response and control is rather straightforward and rather unarguable. I don't think, really, that there is anyone who would question, probably with a few exceptions, that in the normal pattern of use, either for insect control, pathogen control, weed control, the smaller drops are unquestionably more effective.

Then we have to ask ourselves why do we get the results we do with the larger drops. Well, the easy answer is to say that we are overdosing. But if you talk to the people who have set the dosages, talk to the chemical people, talk to the researchers, who have set the dosages on these things — *not necessarily so.* It is based, the dosages are based, of course, on a typical type treatment and probably not the most efficient drop size and certainly not the most efficient application. They have to take into account the many problems that are going to arise in the field.

It is axiomatic, that anybody who wants to go out and make an application carefully, precisely, under the right conditions, with all the things going right as we do as researchers, can probably cut the normal dosage in half and do an excellent job. So watch out for this sort of concept, that perception that you went out and made an experimental application that allowed you to cut the dosage in half . . . that is not exactly how the dosage was set, it was done on a different basis.

Well, in carrying a little bit further into the question, what are we going to do about it or why are we in this predicament? Well, I guess I can only say that this is just simply a function of the thing that we are trying to do — trying to control a biological element by getting involved in the physical processes of moving a material from the aircraft, well, first, to break it up in some atomized degree, moving in then to contact the target insect. These are inefficient systems, there is no question about it. Nobody argues that point either. But what do we have to substitute for it? It is all well to say Hey! it is terrible, you shouldn't do this, you shouldn't do that, but what are you going to substitute for it? We are stuck with what we have got. Where do we stand? Where are we? It is a compromise situation and certainly when we talk to regulatory people in California — and you all are perfectly familiar with our situation there — we are right up against the line in terms of use of pesticides for anything and consequently we cannot go and talk to those people or convince regulatory people that we should be going out and be putting on materials 50% of which we can't account for.

There is no way, and that's why we have to be concerned very much about this. So in terms of trying to resolve this position, it is a compromise situation, and you have to look at the efficacy of the job, realising that you can be more efficacious if you did this and this, and this, but that in order to keep from contaminating the water, the air, the soil . . . .all that goes with this present concept of the public with regard to pesticide use, you have to have some different considerations and probably look at it in a different way. I apologize for taking such a long time in answering your questions.

Jack Barry:

I'd like to make a couple comments to Al's *(Drummond)* comment about helicopter and fixed wing.

We ran a test, several years ago, comparing the Jet Ranger and a Turbo Thrush aircraft, looking at deposition and lateral deposition. We do have a report providing data. We would be pleased to provide this report to anyone who would like to see it.

To comment on the meeting we had in Toronto and that we have a love affair with helicopters in the western United States, I just want to clarify that we like helicopters because some terrain we operate in, well most of the terrain, I should say, is very rugged and we need to be close to the canopy. We would like to use fixed wing aircraft if we could be close to the canopy and be able to fly the contours. We often can't, so we are forced to helicopters. We don't feel that one aircraft is better than the other as far as deposition pattern is concerned.

Al Drummond:

I am glad you can clarify that. I just tried to hit the highlights but you gave all the facts, that's good Jack *(Barry)*. Thank you.

Alam Sundaram:

I have one comment with regard to Dr. Parkin's presentation in relation to the volatility differences in aqueous formulations and I have one question to Dr. Nick Payne.

Dr. Parkin, I was very intrigued about the differences in the slope of the volatility curves of the two aqueous formulations you presented. I found a similar behavior and the only comment I'd like to make is there appears to be two distinctly different types of evaporation of water from the droplet. One formulation containing polymeric, certain polymeric materials, not all polymeric materials, and the mode of evaporation appears to be, when the water evaporates from the outer surface of this spherical droplet that it seems to form a core, a polymeric wall, which actually forms a kind of diffusion. It creates a diffusion process for the material, water inside the core and therefore you have a phenomena similar to the control release but instead of a control release of pesticide, this is a control release of the water through the porous membrane of the polymer, so that is an entirely different phenomena.

The other aspect, distinctly different aspect, relates to the presence of the humectant or anti-evaporant materials that are in the formulation. One particular example: we found that the presence of Dowanol in fenitrothion formulations, especially Dowanol without any other product than fenitrothion, at low temperature, similar to those found during New Brunswick spray operations, the presence of Dowanol actually increases the droplet size and it minimizes the droplet evaporation. Therefore the presence of a humectant retards the evaporation of water, not only retards, but sometimes it absorbs the water from the outside environment.

So I really appreciated the curves that you presented.

Steve Parkin:

The process of evaporation is extremely complex and what I was doing was only highlighting. It is very true to point out that you can get this sort of wall effect occurring. Also you can get very different effects due to viscosity, as Professor Spillman pointed out in his paper this morning. There is circulation within the droplet as the droplet falls, which makes the process extremely complex and by adding anything to the spray, that would change the characteristics, you can change the evaporation rate. It is a field that is up for grabs at the moment to try to sort out some principles because we are all using models of it which I think were developed for materials that we're not actually handling.

Alam Sundaram:

Dr. Payne presented some interesting data and the standard deviations he pointed out definitively tells us something about the variability of foliar deposit. There is something that really concerns me here and that is if you spray . . . the data to me sounded like that, at higher wind speed, you have a higher canopy deposit, which is true, which you explain very well, but what happened to the standard deviation, did it increase; — probably I missed that point.

Nick Payne:

I didn't present standard deviation for the deposit measurements that were made in high wind speeds. Those were made by Joyce et al and he didn't report them if I remember correctly.

Alam Sundaram:

So I didn't miss anything.

But the question I am going to ask you is — Do you think that at high wind speeds, in spite of the fact that the average deposit may be very high, in your opinion, mathematical calculations, do they show there is greater likelihood of higher standard deviation or will this be minimized because, we scientists would like to see the minimization of the standard deviation in all of our sprays because that is the key to having a more uniform insecticidal activity. Can you comment on that please?

Nick Payne:

I can comment on it by giving you my opinion. I cannot recall any evidence that I can readily site as very concrete but I would say that under this condition where you have stronger turbulence that would lead to more rapid cloud mixing and that would, in turn, smooth out the concentration of droplets in the air more quickly than in stable conditions where you've got less turbulence and as a result you have regions of high droplet concentration moving very quickly to regions of nil concentration whereas in the unstable case the cloud is mixed more quickly and maybe you've reduced the variability.

John Ray:

In New Zealand we try to emphasize to the practicing forester and the pilot that you're always going to have drift in any sort of aerial spray operation. It is essential to realize this and there are many situations where, because of drift and possible damage or chemical trespass it is not going to be possible to spray all sites and therefore, in those conditions, the only reasonable thing to do is not to apply a chemical.

The other thing we try to emphasize is, that because you are going to get drift, you must manage it and you must always carry out the operation when there is a positive wind away from sensitive areas.

We try to advocate the use of some form of smoke generation to indicate the direction of the wind and again don't spray under very stable conditions. Those are really the only practical solutions I think we can offer to the forester in the field.

Michel Pelletier:

Only one comment. I think that you presented practical things to do on an aerial spraying program and ways of avoiding drift or potential damage from drift. In fact on every spray operation we should have guidelines to avoid as much as possible drift problems.

Any other questions?

David Oxley:

I have got the same concern that my friend from Scott Paper Company has. If we are talking of drops of 50 microns or less and you have to turn a Micronair at 14 000 RPM, can you do that on an actual application? I was doing a little calculation and it seems to me, that if you are flying at 30 meters and you are having an 8 miles per hour wind, all that stuff will be over 5,000 feet away from you and it will be 15 minutes after you are gone by before it got there.

Is that right? Or is there something else happening, and I think there is, that is getting it down faster and closer?

Steve Parkin:

If I could get to the last point. If you look at the sedimentation velocity table you can calculate quite easily how far the droplet should fall given a particular time sequence. But that is not exactly what happens. What we were trying to explain, I think, is that there are other processes involved than just simply falling and ballistics. We've got atmospheric turbulence which we've been looking at; we've got vortex movement which is also another mechanism which alters the whole process and because of that it is not as clear and simple as we'd like. It is a complicated phenomena, and generally, most of the processes are involved in bringing the stuff down much more quickly rather than keeping it up there. Just using ballistic tends to give you a very very bad case. It ends up that you've got material going around the world. To use a phrase of a colleague of mine, he once said finishing a lecture, he used to pull a stunt, which was: "This is the completely drift-free application" and he used to show a blank slide. It is a bit like that really. There is no such thing as drift-free application and really it's a case of what is practical and what is feasible to do in practice, and unfortunately the simple theories just don't cope and give you a very poor picture. We're trying to devolve something that is more practical than that.

Chairman (*M. Pelletier*):

Are there more questions?

Well, if not I would like to thank everyone who has been here this afternoon and I hope that you have enjoyed this session.

Thank you very much.

SESSION IV

SPRAY CLOUD MEASUREMENT AND ASSESSMENT

LABORATORY EVALUATION OF EMISSION SYSTEMS

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ABSTRACT — The drop size spectrum is one of the most important factors that affects spray behavior. The recent introduction of several new laser instruments has revolutionized the measurement of drop size spectra. However, a pressing problem is the diversity of data from different facilities. Some problems and limitations of different systems are presented. It is now possible to utilize a wind tunnel and laser instrument system to simulate and measure drop spectra from aerial emission systems. Quality of results depends on: a) type of instrument system, b) calibration, c) experimental procedures, and d) analysis of results. A typical drop spectrum is presented to illustrate one technique that can be used to combine data from two probes. Thus, with our PMS system we can cover a range of 1.1 to 2046 μm. One approach to standardization is presented.

RÉSUMÉ — La plage de la dimension des gouttelettes est l'un des facteurs qui influe davantage sur le comportement des aérosols. L'introduction récente de plusieurs nouveaux instruments lasers va révolutionner la mesure des dimensions des gouttes. Toutefois, un problème à résoudre rapidement est la diversité des données obtenues aux différentes installations. Certains problèmes et certaines limitations des divers systèmes sont présentés. Il est maintenant possible de se servir d'une soufflerie et d'instruments lasers pour reproduire et mesurer les gouttelettes de toutes dimensions produites par des émetteurs aériens. La qualité des résultats dépend : a) du type d'instrument, b) de leur étalonnage, c) de la méthode expérimentale et d) de l'analyse des résultats. La présentation du spectre typique des gouttelettes permet d'illustrer une technique utilisable pour combiner les données obtenues au moyen de deux sondes. De cette façon, notre système PMS (système de mesure des particules) permet des mesures sur une plage allant de 1,1 à 2046 μm. Nous présentons une méthode de normalisation des résultats obtenus.

INTRODUCTION

The initial drop size spectrum produced by agricultural aircraft is a basic variable that affects the spray particle trajectories, evaporation, target coverage, pesticide efficacy and off-target losses. Thus, it is recognized that precise drop size spectra data are needed to provide: a) necessary input data for theoretical models, and b) aid in the selection of atomization systems to improve efficacy and reduce environmental contamination. In the past, procedures for measuring drop size spectra from agricultural aircraft relied on collection of drop samples on paper, glass slides, magnesium coated slides or oil immersion cells. The procedures were laborious and may result in numerous errors. However, in recent years several new laser systems have been developed and offer substantial advancements in the accuracy of measuring the drop size spectra. Although several instruments are available, the different instrument characteristics and standard operating procedures have not been established. The quality of drop size spectra data clearly depends on numerous factors. The objective of this paper is to discuss the following factors related to the accuracy of measuring the drop size spectra: type of instrument, calibration, experimental procedures and data analysis.

TYPE OF INSTRUMENT

Numerous models and types of instruments are available for analyzing the drop size spectra. Several of the instruments operate on different principles. Some examples are: the Malvern utilizes a laser and measures the relative angular scattering intensity; the Particles Measuring System (PMS) optical array probe measures the shadow produced by a particle in a laser beam; the PMS, FSSP probe measures the intensity of the forward scattered light in a laser beam; the Aerometrics measures the phase shift as a function of angle for light refracted through drops in an off-axis forward direction; the KLD instrument is based on the heat-transfer from a heated wire to a drop striking the wire; the Bete system is a video imaging system using strobe illumination and digital image analysis.

Unfortunately, the different types of instruments as well as the same instrument used in different laboratories may result in a significant difference in reported drop size for the same spray. Because of the concern over potential discrepancies in reported drop size data, some interested members of the ASTM E29.04 subcommittee on Liquid Particle Size Measurements conducted a "round robin" measurement of the drop size from two selected nozzle types and two nozzle pressures for each nozzle. Results were published in a report by Dodge (1987). The following is an example of one set of results for the Delevan Nozzle tested at 276 kPa and sampled 64 mm from the center line. The four laboratories that measured the "spatial" spectrum (Malvern) resulted in an average Sauter Mean Diameter ($\bar{D}_{32}$) of 133 μm while the average of instruments that measured the "temporal" (PMS, KLD, Aerometrics) spectrum showed an average $\bar{D}_{32}$ of 188 μm or 41% larger than reported by the spatial instruments. Additional tests included in the report by Dodge (1987) indicate that some but not all of the difference in $\bar{D}_{32}$ can be attributed to the difference in spatial and temporal sampling. Also, the report for the above tests showed results from four different laboratories with the Malvern instrument reported a range of $\bar{D}_{32}$ from 87 to 138 μm. The range of results from two different laboratories with the Aerometrics instrument reported a $\bar{D}_{32}$ of 135 and 156 μm. Some of the differences between laboratories with similar instruments may be due to different operational procedures. Hopefully, with more experience, some standard operational procedures can be developed that will minimize the difference in results from similar instruments. At the present time, the ability to obtain quality data is based on experience and is not a "turn key" operation that can be delegated to nontechnical personnel. The selection of the type of instrument should be based on particle size range of interest, type of sampling desired (temporal or spatial), portability and laboratory physical requirements and type of drop size spectrum data desired.

CALIBRATION

Each laboratory should develop a quality control procedure to insure collection of reliable data. One important step is to calibrate the instrument. Since we have two types of PMS probes, we will discuss the general procedures we have utilized with each probe, the FSSP 100 and the OAP-D2GAI.

PMS-FSSP 100 Probe

The FSSP probe is a single particle, light scattering instrument that counts and sizes particles passing through a laser beam. The instrument uses photodiodes to measure light intensity collected from the hollow cone between 3 deg and 13 deg of the forward scattering direction. The response voltage is a function of particle size, refractive index (m), geometry of the collecting optics and wavelength of the laser beam. PMS provided a calibration of the probe for water, based on a smooth average response curve with uniform class sizes for four different response ranges. Table 1 shows a list of the 15 class sizes in each of the four ranges as calibrated by the manufacturer (Man).

Pinnick et al (1981), Bontemps (1983), and Baumgardner (1983) showed the need to carefully recalibrate the PMS forward scattering probe. The studies by Pinnick, et al (1981) showed that the instrument response followed the Mie theory with pronounced oscillations in the response as the drop diameter increases. Thus, the manufacturer's calibration may produce artificial humps or valleys in the distribution pattern. Sidahmed (1987) calculated the Mie scatter curve for our instrument and selected the appropriate groups of class sizes that would minimize errors in classification of drop sizes due to the oscillations. The first step involved calculating the Mie scatter for glass and the maximum % error that would associate with a channel when considering its mean voltage as the experimental response. Based on this, monodisperse glass beads (15 μm) were chosen to be measured with the probe in its most sensitive range. An initial calibration factor ($C = 6.3 \times 10^5$ volts/cm^2) was calculated based on the theoretical response R (cm^2/particle) and the mean voltage for the class size where the maximum counts (number/s) occurred. Next, this factor was used to position the pulse height discriminator levels of range 1 relative to the theoretical response curve for glass (Figure 1). As seen in Figure 1, measurements with two glass bead sizes 8μm (just below a discriminator level) and 30.6μm (just above a discriminator level) showed that no adjustment for C was necessary. Additional monodisperse beads were measured (39.6, 47.8 and 88.4 μm) to verify that the response of each fell in the appropriate channel based on the above calibration factor. Figure 2 illustrates the calibration data with a calibration factor of $C = 6.3 \times 10^5$ volts/cm^2. The last step involved calculating the Mie scatter curve for water and the appropriate discriminator levels for each channel based on the above calibration factor. Figure 3 illustrates the class size boundaries that were selected for range 0 based on Mie theory. As shown, several channels were grouped together in the multivalued region to avoid erroneous counts. Table 1 summarizes the new class sizes based on Mie theory (for each of the four ranges) for water drops. The same procedure can be used for other materials by calculating the Mie scatter curve with the appropriate index of refraction and selecting appropriate groups of channels to avoid multivalued areas.

PMS-OAP-2DGAI

The optical array probe had 64 diodes in a linear array across the beam. The optics on our probe provided a magnification of the beam to represent 33 μm between each diode. The maximum number of shadowed diodes for each image is used to classify the drop size. The manufacturer calibrated the system with 1570 μm

TABLE 1: The channel size specifications (in microns), for water drops, listed by the manufacturer (Man.) and based on the Mie scatter theory and glass bead calibration (Mie).

	Range 0		Range 1		Range 2		Range 3	
Channel	Man.	Mie	Man.	Mie	Man.	Mie	Man.	Mie
1	1-2	1.1-	2-4	2.6-	2-5	2.6-	5-11	4.7-
2	3	-2.8	6	-	8	-6.9	17	-17.2
3	4	2.8-	8	-6.9	11	6.9-	23	17.2-
4	5	-	10	6.9-	14	-	29	-
5	6	-4.8	12	-	17	-17.2	35	-38.1
6	7	4.8-	14	-	20	17.2-	41	38.1-
7	8	-6.9	16	-15.4	23	-	47	-
8	9	6.9-	18	15.4-	26	-27.6	53	-58.3
9	10	-	20	-20.5	29	27.6-	59	58.3-
10	11	-	22	20.5-	32	-	65	-71.7
11	12	-13.2	24	-	35	-38.1	71	71.7-
12	13	13.2-	26	-27.6	38	38.1-	77	-84.3
13	14	-	28	27.6-	41	-	83	84.3-
14	15	-	30	-	44	-	89	-
15	16	-15.4	32	-34.4	47	-51.7	95	-102.7

steel spheres. Results from the PMS probe indicated 1571 μm. The OAP registers a diode, as shadowed, if its voltage output decreases by 50% or more. Baumgardner (1987) discussed studies he conducted to simulate the percentage of coverage for the diodes at the edge of each drop size for various positions of the drop relative to the diodes. He concluded, on the average, particles could be undersized approximately one size channel.

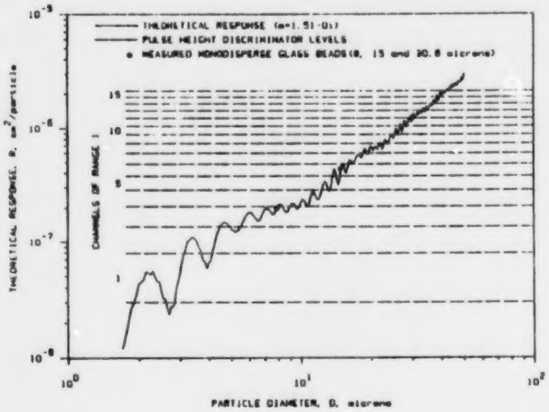

FIGURE 1: THE POSITIONS OF THE FSSP-100 PULSE HEIGHT DISCRIMINATOR LEVELS OF RANGE 1 RELATIVE TO THE THEORETICAL MIE SCATTER RESPONSE CURVE FOR GLASS, BASED ON A CALIBRATION FACTOR $C = 6.3 \times 10^5$ VOLTS/CM^2

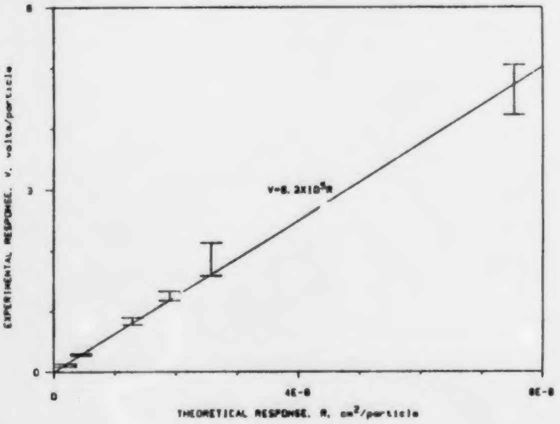

FIGURE 2: THE FSSP-100 CALIBRATION CURVE. THE MEASURED PARTICLES WERE 8, 15, 30.6,39.6,47.8 AND 88.4 mm MONODISPERSE GLASS BEADS. THE ERROR BARS REPRESENT THE UPPER AND LOWER DISCRIMINATOR LEVELS FOR THE CHANNELS WHERE MAXIMUM COUNTS (NUMBER/S) OCCURRED.

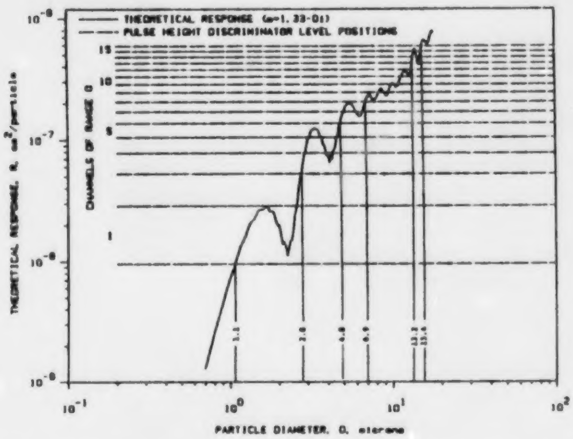

FIGURE 3: THE POSITIONS OF THE FSSP PULSE HEIGHT DISCRIMINATOR LEVELS OF RANGE 0 RELATIVE TO THE THEORETICAL MIE SCATTER RESPONSE. THE VERTICAL LINES REPRESENT THE NEW SIZE-CLASS BOUNDARIES (FOR RANGE 0) BASED ON MIE SCATTER.

EXPERIMENTAL PROCEDURES

Wind Tunnel

A wind tunnel is necessary to simulate the aerodynamic forces that impact on the liquid ligaments during the atomization process of nozzles operating on agricultural aircraft. We constructed a straight through wind tunnel with an exhaust blower. The tunnel is described by Yates et al. (1985) and consists of a 0.61 × 0.61 × 2.4 m long test section with glass on both sides. The maximum velocity is 240 km/h. The unit produces a nearly uniform velocity profile with a turbulence level of 1.3% in the central part of the tunnel.

Scanning System

One vital part of the spray analysis facility is a method to rapidly assess and determine the overall temporal drop size spectrum produced by the atomization system. We developed an X-Y scanning system (Yates et al. 1985) that could move the nozzle through a series of parallel traverses to assess the entire spray pattern. The system utilizes a microprocessor with two stepping motor drives and can be rapidly programmed to vary the length of traverse, number and spacing of traverses and speed. A typical test is with the nozzle 18 inches from the probe, a scan speed of 1 cm/sec, 8 traverses and a total scan time of 8 minutes.

Instrument Adjustments

Most drop size spectrometers have critical operational parameters that require experienced operators to monitor and adjust to obtain quality data for a variety of experimental conditions. The following are important adjustments of the PMS-2DGA1 probe.

Slice Rate. The slice rate controls the frequency the diode data is recorded. The frequency should be adjusted to record at least two slices of data for the smallest drop size. For a 33 μm drop, this would require collection of data for every 11 μm movement of the particles. At a speed of 160 km/hr, the necessary slice rate is 4.0 mHz. A good rule to follow for our unit is to adjust the slice rate to obtain a particle image about three times as long as the height on the screen.

Bulk Area Ratio (BAR). This value represents the criteria that is used to reject image events with multiple particles. The ratio of total pixels to shadowed pixels is calculated for each particle event. If the value is larger than the value set in BAR, the event is rejected. Results from our tests indicate a BAR of 1.5 is appropriate with a mechanical sample width of 1 cm. Larger sample widths require a larger BAR to accept most single particles and consequently may possibly accept more multiple particle images.

Mechanical Depth of Fields (MDF). This represents the width of sample zone. The standard probe has a sample width of 6.1 cm. This width of sample zone has several disadvantages. For example, in dense spray patterns, excessive drop images are rejected because of multiple particles in the beam: the calibration studies show an error as the particle location moves from the focused area at the midpoint; and greater theoretical depth of field corrections are required for the smaller size classes if a wide sample width is used. Thus, we designed extension tubes to limit the sample width to 3, 2 or 1 cm. In very dense sprays, we have found the 1 cm sample width to be superior.

ANALYSIS OF RESULTS

The PMS — DAS 11C computer system was used to control the probe and acquire the basic drop size distribution data. After each test, we routinely transfer the basic data to the memory of a laptop Epson PX-8 computer. This was found desirable because the output format of PMS-DAS-11C could not be changed by the user and the entire system was too bulky to transport from the laboratory to the office or computer areas. Thus, the Epson PX-8 and an Epson FX80 printer is used to immediately print out the desired results of the test. We can normally store one day's records, up to about 50 tests, directly in the Epson PX-8 memory (128k bytes RAM). Since the Epson's RAM is nonvolatile, the computer can be taken to the office and data transferred directly from RAM to an IBM PC/AT for further analysis and storage. Table 2 shows a typical output record for the PMS-OAP-2DGAI probe. In the office area we routinely use an HP 7475 plotter to illustrate the drop size data. Figure 4 shows the standard graphs we plot for each test. A similar type output but with different scales is used for output from the PMS-FSSP 100 probe.

If the % volume in either the smallest or largest size class for any test is greater than a few percent, it may be desirable to conduct another test with probe adjustments made to measure the truncated portion of the drop spectrum. Table 3 shows the truncated data for a fine drop size spectra that was measured with a PMS-2DGAI probe. Sidahmed (1987) has developed software to combine two or more drop size spectra if an overlap area exists between the data sets. Table 4 and Figure 5 illustrate the resolution that can be achieved if three data sets obtained with the above Delavan nozzle are combined. In this case, data was taken with the FSSP-100 on range 2 (2.6–51.7 μm) and range 3 (4.7–102.7 μm) and the OAP-2DGA probe with a range of 28–2046 μm. The range 2 data was included to enable resolution down to 2.6 μm. Our system could potentially go down to a resolution of 1.1 μm on range 0. Range 2 was certainly adequate for this spectrum. The overlap region used for merging range 2 and range 3 was 17.2-38.1 μm. Because the first two channels of the OAP has greater uncertainty, the data from 28-89 μm was not used, and the overlap region used for merging the OAP and FSSP (range 3) data was 89.0-102.7 μm.

TABLE 2: Typical record of drop size spectra recorded from a test in the wind tunnel with the OAP-2DGA1 probe.

Nozzle	8004	Slice Rate	4 M MHz
Angle to Airstream	90 degrees	AVG	100
Spray Pressure	40 psi	DFM	1 cm.
Airspeed	120 mph	BAR	1.5
Flow Rate	.4 gpm	Distance to Probe	36 cm.
Tank Mix	Flowable DIPEL ABG-6167	Sample Interval	360 sec.
		Number of Samples	1
		Number of Scans	6
FILE: C:/PMS/DATA/05208712.000		Scan Spacing	5.2 cm.
Number of Tests Combined: 3		Scan Length	25 cm.

Upper Limit	N(Raw)	N/Sec	Gm/Sec	% N	% Vol.	Accumulated % N	Accumulated % Vol.
28							
56	6258	9.76E+06	0.32	43.31	1.23	43.31	1.23
89	9631	3.91E+06	0.78	17.35	2.98	60.66	4.21
122	7772	3.27E+06	1.98	14.49	7.60	75.16	11.81
154	6041	2.29E+06	3.13	10.16	12.01	85.31	23.82
187	4251	1.27E+06	3.29	5.64	12.60	90.95	36.42
220	3961	913783	4.00	4.06	15.32	95.01	51.74
252	3332	588469	4.01	2.61	15.37	97.62	67.11
284	1861	258790	2.60	1.15	9.96	98.77	77.08
318	1199	124735	1.79	0.55	6.87	99.32	83.95
351	746	69469	1.36	0.31	5.21	99.63	89.16
382	505	39974	1.02	0.18	3.91	99.81	93.07
414	287	21862	0.72	0.10	2.76	99.91	95.83
447	169	11316	0.47	0.05	1.81	99.96	97.64
479	93	6035	0.31	0.03	1.20	99.98	98.84
512	45	2402	0.15	0.01	0.59	99.99	99.42
545	16	606	0.05	0.00	0.18	100.00	99.60
578	6	314	0.03	0.00	0.11	100.00	99.71
611	0	0	0.00	0.00	0.00	100.00	99.71
644	3	581	0.07	0.00	0.29	100.00	100.00
Total	4.62E+04	2.25E+07	26.09				

Total accepted raw particles / Total images = 46176/56998 = 81.0%

Number mean dia. = D_{10} 90.25 μm
Volume mean dia. = D_{30} 130.33 μm
Sauter mean dia. = D_{32} 182.33 μm

$D_{N.1}$ < 56 μm
Number median dia. = $D_{N.5}$ 68.99 μm
$D_{N.9}$ 181.72 μm

$D_{V.1}$ 114.08 μm
Volume median dia. = $D_{V.5}$ 216.14 μm
$D_{V.9}$ 357.99 μm

Relative span = 1.13

CONCLUSIONS

Quality drop spectra data can be obtained today if care is taken to: select the appropriate equipment; use experienced professionals to operate, calibrate, and adjust the systems; and the data is analyzed and reported in a manner required by the end user.

We believe most drop size equipment can obtain excellent reproducibility by collecting sufficiently large samples. Thus, data from a single laboratory can likely provide an excellent comparison of changes in drop spectra between different tests. However, one should be cautious in trying to make fine comparisons of absolute values obtained from different laboratories, particularly if different types of instruments are employed. The PMS system measures the N/sec and calculates the volume/s for each size category. Thus, one good independent check on the accuracy of the system is to compare the total vol/s obtained from the drop spectrum data with the nozzle flow rate.

One approach that could be used to aid in interpreting the data from different laboratories is to select a "standard" nozzle and test conditions. Results of tests with the "standard" could be used to estimate the deviation of another laboratory's results compared to their measurements.

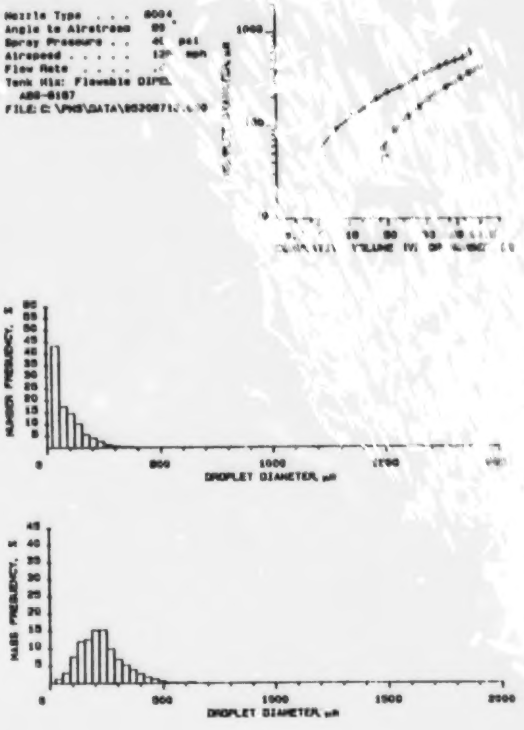

FIGURE 4: TYPICAL PLOT OF THE DROP SIZE DATA PRESENTED IN TABLE 2.

TABLE 3: Drop spectrum data from a Delavan WDB solid cone simplex-swirl atomizer in static laboratory conditions at 689 kPa pressure. Measurements were with the OAP-2DGA1 probe.

Lower Diameter (microns)	Upper Diameter (microns)	Number Density (/micron)	Volume Density (/micron)	Accumulated Number	Percentage Volume
28.0	56.0	.1229E-01	.4332E-03	34.3995	1.2129
56.0	89.0	.3332E-02	.5721E-03	45.3965	3.1009
89.0	122.0	.5824E-02	.3001E-02	64.6164	13.0044
122.0	154.0	.4682E-02	.5342E-02	79.5995	30.0975
154.0	187.0	.3258E-02	.6981E-02	90.3494	53.1335
187.0	220.0	.1846E-02	.6709E-02	96.4426	75.2729
220.0	252.0	.7570E-03	.4282E-02	98.8649	88.9737
252.0	284.0	.2532E-03	.2095E-02	99.6751	95.6770
284.0	318.0	.6970E-04	.8168E-03	99.9121	98.4539
318.0	351.0	.2082E-04	.3346E-03	99.9808	99.5581
351.0	382.0	.4516E-05	.9539E-04	99.9948	99.8538
382.0	414.0	.1449E-05	.3920E-04	99.9994	99.9792
414.0	447.0	.1839E-06	.6293E-05	100.0000	100.0000

Number mean dia. $= \bar{D}_{10} = 104.0$
Volume mean dia. $= \bar{D}_{30} = 132.7$
Sauter mean dia. $= \bar{D}_{32} = 164.0$

$= D_{V.1} = 112.0$
Volume median dia. $= D_{V.5} = 182.5$
$= D_{V.9} = 256.9$

Relative span $= 0.79$

TABLE 4: Combined drop spectra data from a Delavan WDB solid cone simplex-swirl atomizer in static laboratory conditions at 689 kPa pressure. The three tests combined were with a FSSP-100 on range 2 and 3, and the OAP-2DGA1 probe.

Lower Diameter (microns)	Upper Diameter (microns)	Number Density (/micron)	Volume Density (/micron)	Accumulated Number	Percentage Volume
2.6	6.9	.4268E-01	.6066E-05	18.3531	.0026
6.9	17.2	.1527E-01	.3477E-04	34.0772	.0384
17.2	38.1	.1126E-01	.2994E-03	57.6126	.6642
38.1	58.3	.5896E-02	.7585E-03	69.5223	2.1964
58.3	71.7	.3818E-02	.1166E-02	74.6379	3.7589
71.7	89.0	.2816E-02	.1626E-02	79.5096	6.5724
89.0	102.7	.2186E-02	.2129E-02	82.5038	9.4890
102.7	122.0	.2186E-02	.3436E-02	86.7220	16.1210
122.0	154.0	.1757E-02	.5150E-02	92.3445	32.6018
154.0	187.0	.1222E-02	.6731E-02	96.3786	54.8125
187.0	220.0	.6929E-03	.6469E-02	98.6650	76.1588
220.0	252.0	.2841E-03	.4128E-02	99.5741	89.3688
[illegible]	284.0	.9500E-04	.2020E-02	99.8781	96.8318
[illegible]	318.0	.2616E-04	.7875E-03	99.9670	98.5093
[illegible]	351.0	.7313E-05	.3226E-03	99.9928	99.5739
[illegible]	382.0	.1696E-05	.9197E-04	99.9980	99.8590
382.0	414.0	.5439E-06	.3780E-04	99.9996	99.9800
414.0	447.0	.6900E-07	.6067E-05	100.0000	100.0000

Number mean dia. $= \bar{D}_{10} = 53.2$
Volume mean dia. $= \bar{D}_{30} = 96.9$
Sauter mean dia. $= \bar{D}_{32} = 153.6$

$= D_{V.1} = 104.2$
Volume median dia. $= D_{V.5} = 179.8$
$= D_{V.9} = 255.1$

Relative span $= 0.84$

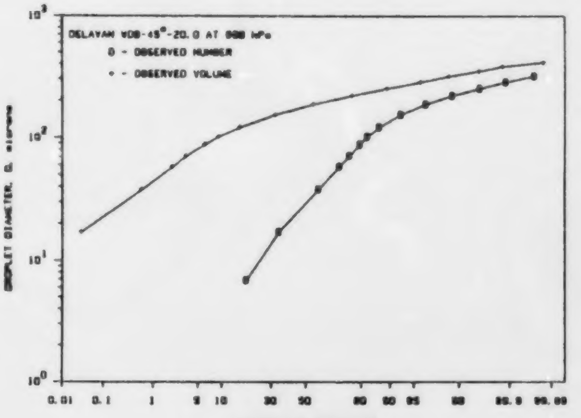

FIGURE 5: COMBINED CUMULATIVE DROP SIZE SPECTRA. (DATA FROM TABLE 3). DATA COMBINED FROM THREE SETS OF OVERLAPPING DATA; FSSP-100 RANGE 2 AND 3, AND OAP-2D DATA.

The future looks bright for further improvements and knowledge of systems to accurately measure drop size spectra.

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QUANTIFICATION OF SPRAY CLOUD MATERIALS WITHIN AND DOWNWIND OF RESEARCH AREAS

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ABSTRACT — The process necessary to adequately sample and quantify aerosols and vapors resulting from forest spray operations is complex. Careful consideration must be given by research, operational and monitoring personnel regarding the strengths and limitations of a wide variety of samplers or sampling instrumentation that may be used within and downwind of a forest area to be sprayed with pesticides or other test solutions. No one sampler will satisfy all of the experimental requirements of all spray programs. Thus, the selection should be limited to those samplers that will satisfy most of the experimental, cost, and logistic requirements of a spray program. Proper sampler selection for forest spray programs involves three major considerations. First, the sampling devices most often used today to detect and quantify spray materials are reviewed. This includes a variety of deposition, filter, impaction and rotating samplers. The utility of bubblers, solid sorbent tubes, etc., as vapor samplers is also presented. Second, more sophisticated and complex instrumentation that has been or may be used in spray programs to sample aerosols and vapors will be shown. This includes fieldable atomic absorption spectrometers, long path infrared spectrometers, flame photometric detectors, LIDAR, etc. Most of these devices are best used to monitor the downwind drift of sprayed materials. Finally, cost, size, transportability, support equipment, and personnel needed to use or operate the aforementioned sampling equipment is included to assist researchers and operations personnel in planning their spray programs.

RÉSUMÉ — Le procédé nécessaire pour échantillonner et doser convenablement les aérosols et les vapeurs produits lors du traitement des forêts par pulvérisation est complexe. Le personnel chargé de la recherche, des opérations et du contrôle doit étudier attentivement les points forts et les points faibles d'une grande variété d'échantillonneurs ou d'appareils de prélèvement susceptibles d'être utilisés à l'intérieur de la zone forestière devant être traitée avec des pesticides ou avec d'autres solutions expérimentales, ou sous le vent par rapport à cette zone. Aucun échantillonneur ne répondra à toutes les exigences expérimentales de tous les programmes de pulvérisation. Ainsi, la sélection devra se limiter aux échantillonneurs qui satisferont la plupart des conditions d'un programme de pulvérisation donné, au point de vue des aspects expérimentaux, de la logistique et des coûts. Trois considérations importantes interviennent dans le choix d'un appareil de prélèvement approprié, dans le cas des programmes de pulvérisation forestière. En premier lieu, on passe en revue les dispositifs de prélèvement employés le plus souvent de nos jours pour déceler et doser les produits pulvérisés. Parmi ces dispositifs, on compte une variété d'échantillonneurs à sédimentation, à filtre et à impact, ainsi que des échantillonneurs rotatifs. On souligne également l'utilité des barboteurs, des tubes à sorbant solide, etc., pour le prélèvement d'échantillons de vapeurs. En deuxième lieu, on décrit des appareils plus perfectionnés et plus complexes qui ont été ou qui pourraient être utilisés lors de traitements par pulvérisation pour prélever des échantillons d'aérosols et de vapeurs. Ils'agit entre autres de spectromètres d'absorption atomique utilisables sur le terrain, de spectromètres infrarouge à long chemin optique, de détecteurs à photométrie de flamme, de lidar, etc. La plupart de ces appareils conviennent le mieux au contrôle des produits pulvérisés entraînés par le vent. En troisième lieu, on fournit les renseignements suivants pour aider les chercheurs et le personnel chargé des opérations à planifier leurs programmes de pulvérisation : coût et taille des appareils, possibilité de déplacer ces derniers, matériel de soutien et personnel nécessaire à l'utilisation ou à l'opération des appareils de prélèvement susmentionnés.

INTRODUCTION

The process necessary to adequately sample and quantify aerosols and vapors resulting from forest spray operations is complex. Many factors can impact upon the conduct and ultimately the success of an operation. To mention a few: the location and accessibility of the spray area, equipment availability and transportability, the expertise of test personnel required to operate the selected sampling equipment, proximity of the spray area to productive agricultural areas, potential impact upon watershed areas, etc. Careful consideration must also be given by research, operational, and monitoring personnel regarding the strengths and limitations of available samplers and sampling instrumentation. No one sampler will satisfy all experimental requirements of all test programs. Thus, the selection should be limited to those samplers that will satisfy most of the experimental, cost, and logistic requirements of a specific spray program.

It must be mentioned in passing that regulatory requirements and public concern may limit the scope of a spray operation. Although these factors are often more political than scientific in nature, they can drastically alter a forest manager's planning. It is impossible to state with 100 percent certainty to interested groups that no adverse affects will occur. Unfortunately, they may expect this.

For simplicity, in this paper we have considered three major aspects that affect spraying operations. First the sampling devices most often used today to detect and quantify sprayed materials are reviewed. In actual fact, these devices represent the state-of-the-art for most spray operations and most of our discussion is focused on these samplers. Second, more complex and/or sophisticated and costly instrumentation that may be used or are used on selected spray operations are briefly discussed. Finally, cost, size, transportability, support equipment, and personnel needed to use or operate the aforementioned sampling equipment is discussed.

This paper is not intended to be an exhaustive listing of sampling techniques and devices. Nor is it intended to be a theoretical discussion. Rather, it is a review of those devices that have received the greatest usage and those that are being actively evaluated.

COMMONLY USED SAMPLING DEVICES

One of the first tasks in planning experimental or spray operations is the selection of samplers and/or sampling equipment. Before selection of samplers can begin the type of chemical to be released must be considered. Although this is an obvious consideration its implication in the sampler selection may not be quite so obvious. First and foremost, the levels of detection needed in order to meet the objectives of the spray operation must be stated by the program manager or by the developer of the delivery system. Also, the intended use of the delivery system, pesticide, etc. will, in the main, determine the detection levels possible. For example, the lower detection limit of an analytical method for a specific compound affects the evaluation of a system and/or spray operation. If the analytical method lacks sensitivity, then the sampling schedule or type of sampler must be changed. The factors to be considered in sampler selection have been reviewed in detail elsewhere (Ekblad 1979). A brief summarization of some of these factors are listed in Table 1.

Most of the above factors are self explanatory. However, accountancy merits further explanation. The mass recovery of chemicals disseminated in spray operations varies widely. Mass recovery is the percent of the mass of the sprayed chemical accounted for after diffusion and calculations are performed using the quantitative chemical analysis data. Many of the factors listed in Table 1 can adversely affect the mass recovery. In some cases, the recovery may be as low as 20 percent (Dumbauld and Rafferty 1976). This means a large part of the total mass is unaccounted for through evaporation, drift, and/or inadequacy of the selected sampling technique. In regard to this last point, examples of inadequacy of the sampling technique are: under-sampling of an aerosol cloud because of an unexpected small aerosol size distribution (dissemination problems), an unfavorable wind field (meteorological or terrain problems), or selection of the wrong sampler. Regardless of the cause, if the operational personnel must account for the total mass of sprayed material they must be aware of potential sampling/sampler problems and the strengths of each in order to account for the mass of sprayed chemical.

The samplers discussed in this section are point samplers. They sample a very small area (not actually a point) in the immediate surroundings of the sampler. Many of one or several types (depending upon the scope and objectives of the test or spray operation) are normally used on each dissemination trial. This is necessary to determine concentration, dosage, deposition levels, etc. within and downwind of a target area. Both aerosol and vapor sampling devices are discussed.

TABLE 1: Factors Affecting Sampler Selection

1. Pesticide to be sprayed.
2. Expected particle size and application rate.
3. Sampling time and air volume necessary to meet sensitivity limits associated with analytical methods or sampling instrumentation.
4. Sampler collection efficiency.
5. Potential for background contamination.
6. Simplicity of operation, cost, transportability, availability, and personnel expertise.
7. Terrain and atmospheric condition.
8. Accountancy

Sedimentation/Fallout Samplers

Except for the natural collectors such as needles or leaves, sedimentation or fallout samplers are the simplest of all the sampling devices used by the Forest Service and other testing agencies. These samplers can be filter paper, jars, cardboard stock, stationary, cover stock materials such as Kromekote or Mylar sheets, etc. The fallout samples are often used only as visual markers which permit operational personnel to see where the sprayed material lands. With the exception of Kromekote cards, these samplers are of little value in determining the droplet size spectra because the stains that form on the surfaces of filter paper or cardboard stock, etc. usually are irregular in shape and the stain boundaries are feathered and ill defined. In some circumstances however, these samplers can be used for mass analysis. Filter paper samplers or Mylar sheets are normally used rather than the other types of materials. In most operations conducted at Dugway, the filter paper sampler is the fallout sampler of choice when low vapor pressure chemicals are disseminated or if the spray program is conducted during the winter. The sampler is constructed by stapling together two or three sheets of filter paper. The multiple sheets are used to minimize loss of test solution caused by soaking through only one layer and deposition on the holder. The type of filter paper is not critical. The size varies considerably but 3 × 7 inch (8 × 16 cm) is an example of a representative size. The filter papers are placed in steel or plastic holders and positioned horizontally on the ground or just above the ground cover. After the spraying is completed, the filter papers can either be placed in screw-cap test tubes and solvent added in the field or they can be placed in sample carrying boxes, transported to the laboratory, and the filter papers removed from the holders and the solvent addition, extraction, and analyses performed.

The filter paper, cardboard stock, etc. have been largely replaced as mass samplers by glass or aluminum plates or by Mylar sheets in the spray programs conducted by the Forest Service. (Hurtig and Perry 1950; Isler 1963). After the droplets settle or impact on the sampler surface the samplers are returned to the laboratory and the droplets washed from the collectors and the quantity of tracer or sprayed chemical in the washings are determined using an appropriate analysis method.

A completely different type of sedimentation or fallout sampler that is used for mass collection is the liquid filled sampler. A liquid filled sampler may be a petri dish, a jar, etc. A tracer need not be added to the spray formulation if a liquid filled sampler is used, because evaporative loss of the formulation of interest is greatly reduced, thereby permitting direct analysis. Being able to directly analyze for the pesticide or herbicide of interest instead of relying on an indirect method or analysis such as the use of a chemical tracer, usually results in a large increase (sometimes as great as 50×) in apparent sensitivity. The principal drawback in using liquid filled samplers is spillage, leakage, and breakage. A new and improved liquid filled sampler was recently described by Long and Houle (1985). This sampler can be filled in the laboratory or the field, contains a minimum volume of solvent, thereby improving the overall detection levels, has a reduced "edge" effect, and can be uncovered, positioned, and recovered with one hand. The lid seals, reducing leakage and the sampler is made of plastic, eliminating breakage.

Kromekote cards are the sedimentation sampler most often used to determine the mass median diameter (mmd) or the mass volume diameter (mvd) of an aerosol cloud. They are usually placed horizontally on the ground or raised slightly above the ground cover. The droplets landing on a Kromekote card spread and form stains the size of which depends upon the composition of the sprayed solution and its solubility, contact angle, etc. on the Kromekote card (a dye tracer must be added to the formulation). This relationship is known as the "spread factor" for that particular solution on Kromekote cards. The spread factor must be determined for each formulation and batch of sampler cards. It must also be remembered that the spread factor changes with droplet size.

Forest managers also need a detector paper that can be used with non-dyed pesticides or herbicides formulations. One of the first attempts to fulfill this requirement was the preparation of malathion sensitive cards (Skagg and Cowan). The card was prepared by dipping Kromekote cards in Sudan Black BR dye. Droplets of malathion landing on these cards produce visible stains. This technique has been extended to other types of detector paper that may be used with different undyed chemicals. A good pictorial review of this aspect of sampling technology has been prepared by Kautz and Ekblad (1984).

Foliage has been used as sedimentation samplers. They are often used in conjunction with ground fallout samplers to establish the relationship between the number of droplet stains on foliage and the associated sedimentation samplers to insect mortality. Many spray evaluations have been limited to just examination of the foliage and not insects. There are a few notable exceptions where both insects and foliage were examined (Himel and Moore 1967, Barry et al. 1977 and Barry 1974).

Dyed and some undyed insecticides will leave a visible stain on the foliage that may be visible for over a week. The stability of the foliage stain is a distinct advantage over the use of cards where sun fading is a problem. In addition, artificial foliage (aluminum coils) samplers have been used in some experimental programs. They appear to be effective in mimicking the natural needles in collection efficiency. Comparisons at various sampling heights within the tree (Sundaram et al. 1986) have been conducted. However, the mass recovery obtained from the metal coils is significantly higher than that recovered from the natural collectors. This may be due to soaking of the formulation into the natural surface, or binding, etc. This sampler merits further investigation.

Although, fallout samplers are simple to use, inexpensive, transportable, etc. there are a number of potential problems that must be taken into account before the data provided by these samplers can be considered credible. When they are used for mass analysis, the vapor pressure of the compound is important. Large losses can result after collection due to evaporation of the chemical from the sampler surface, even if the compound has a moderately low vapor pressure. This loss can be minimized if an indirect measurement is performed using a chemical dye tracer. The tracer is usually a solid organic dye that is soluble in the spray formulation. After dissemination, if the carrier evaporates, the tracer remains on/in the sampler and is not lost. However, this technique also has problems because of the fading or photolytic reactions of the tracer with sunlight. In some cases, no longer than 15-30 minutes exposure can result in a significant apparent loss of tracer. This causes errors in the quantitative results and can also render spot sizing data meaningless as shown by the information presented in Table 2. This deleterious effect can be reduced in magnitude by the addition of stabilizers or light scavengers (primarily ultra-violet scavengers) to the spray formulation. However, the amount added must be as small as possible in order to obtain the desired affect without altering the physical properties of the chemical to be sprayed. (Akesson and Yates 1981, Houle et al. 1969)

TABLE 2: Change in Stain Size as a Function of Sunlight Exposure

Exposure Time (Minutes)	Stain Size (µm)[1]	
	DF504[2]	Rhodamine B[3]
0	110.5	133
15	92.7	124
30	90.2	120
45	unreadable	113
	unreadable	108

[1] Size was determined by an automatic spot counting and sizing device (ASCAS).

[2] DF504 is a fluorescent dye that was added to diethylpthalate (DEP).

[3] Rhodamine B is a Fluorescent dye that was added to DEP.

The use of light stable dyes (visible or fluorescent) has been suggested. We have not found a truly light stable dye. For example, it has been our experience that dyes such as Rhodamine B or DuPont Oil Red may be light stable when sprayed at night, under cloud cover, or lower elevations, but are very unstable at higher altitudes where the solar radiation is more intense or during sunlit daylight hours. In addition, when fluorescent dyes are used, even though an increase in the sensitivity of the analysis results, the data may be erroneous due to background interference from plant chlorophyll (Neisess 1978). These dyes also appear to be more sensitive to photolytic decomposition than non-fluorescent dyes.

Most of the evaporative and surface photolytic reaction problems are eliminated when metallic salts are used as a tracer. Manganese salts have been extensively used. However, these salts are added mainly to water base solutions and are of little use in oil base insecticide formulations because of limited solubility. It is possible that organo-metallic complexes could be substituted for the inorganic salts thereby improving the solubility of the metallic compound in some oil base formulations.

As mentioned earlier, Kromekote or chemically sensitive paper show the droplet sizes that deposits upon the ground or at some pre-selected sampling position. These positions are at known distances downwind from the flight line or release point. Our task in assessing the results of a spray operation would be greatly simplified if idealized droplet trajectories and laminar flow conditions existed in the "real" world. Then only one droplet size (or a very narrow range of droplet sizes) would be found at each sampling position and mass recovery calculations would be quite simple. However, quite the opposite is true. Each fallout card usually collects a mixture of droplet sizes. The degree of mixing depends upon the wind turbulence in the target area. Thus, a portion of the small droplet population is driven toward the ground much earlier than expected and some of the larger droplets are found at downwind distances much greater than expected.

In spite of the above problems, the simplicity, portability, and cost of the sedimentation samplers discussed above have resulted in their extensive use in forest spray operation or in experimental test programs. These samplers provide the data necessary to achieve the objectives of most spray operations if the limitation of each are taken into account. An excellent review of recent forest spray operations and the utility of Kromekote card and other sedimentation samplers was prepared by Barry (1984). These samplers have also been very effectively used to evaluate aircraft and associated spray devices (Barry et al. 1982, Barry et al. 1984, Cadogan et al. 1986).

Impaction and Suction Samplers

Impaction

Impaction samplers are an extension of the sedimentation samplers. They are generally grouped into two classifications; passive and rotating.

Passive Samplers

This class of sampler depends upon the inertia of the droplet. This is a function of the droplet mass and velocity. These samplers are in the form of cylinders, ribbons, small plates, etc. Cylinders are widely used and often are just beverage cans wrapped with the collecting medium (Mylar, Kromekote, filter paper etc.). They can be used for both droplet sizing and mass collection. It is recommended that small cylinder sizes be used because the smaller sizes divert the air streamline much less than larger cylinder or bluff objects such as plates. In addition, plates or flat samplers must be oriented into the wind in order to minimize sampling errors associated with misorientation. This is difficult to do during the complete course of a test.

The collection efficiency of these samplers is highly dependent on droplet mass and can vary widely depending upon the wind speed. This is especially true of the beverage can and flat plate samplers. The lower the windspeed the poorer the collection efficiency because the small droplets ($< 100\ \mu m$) have very little momentum and will follow the streamline around the sampler. These droplets may drift for long distances from the application site (Yates and Akesson 1973). As the wind speed increases, imparting a greater momentum to the droplets, the collection efficiency improves for small droplets. But, another complicating factor is wind turbulence. Turbulence is a variety of windspeeds and directions occurring in and around trees and other objects within the target area. Thus, the wind may come from all directions during the course of the sampling period. This is demonstrated by the observance that droplets, especially the smaller ones, can be found on the backside of the sampler or the side away from the prevailing wind direction.

Ribbons, strings, and pipe cleaners have been used as passive impaction samplers and offer an advantage over the cylinder in that they are nearly omnidirectional and perturb the air flow only minimally. Because the surfaces of these samplers are small, only a small mass of the sprayed chemical may be collected. Unless the chemical can be dissolved from these samplers using a minimum volume of solvent and/or unless a sensitive analytical method exists, the required levels of detection may be such that a larger collection surface or different sampler must be used. Also, considerable post collection evaporative loss can occur with samplers such as pipe cleaners. We have found that this loss can be minimized if the pipe cleaner is dipped in a low volatility solvent such as hexylene glycol before placement in the field.

The size, weight, and cost of the impaction samplers discussed above make them very attractive to operational personnel. They require no power or special skills to use. They are readily transportable to the field and the laboratory for spot counting or mass analysis. They are easy to string along ropes, tethers or mooring wires of balloons and may be placed at various locations and heights in a target tree. If the sampling efficiency problems mentioned above are considered and if the impaction samplers are handled in the same manner as the fallout or sedimentation samplers to minimize sun fade, chemical evaporation, etc. they are very reliable. Examples of tests or spray operation on which they have been used are listed below (Barry 1984, Barry et al. 1984, Sundaram et al. 1986).

Rotating Samplers

The rotating sampler (Rotorod) is a small rod, cylinder, cup, or filament connected to an arm that rotates around an axis parallel to its own axis. The rotating shaft is turned by a small electric motor. The sampler is light weight and requires a power source (battery). The high rotational speed of the arm normally masks the ambient windspeed and as a result, the rotating impactor can efficiently sample even the small droplet sizes. Some droplet sizing data can be obtained from the rotating impactor provided it is not overloaded. If mass analysis is intended (integrated mass) then concern must be given to evaporative losses. This problem is minimized by the use of an appropriate tracer.

Rotorod samplers must be calibrated with each range of droplet sizes. Thus, their usage is complicated by inefficient sampling because of unexpected large or small droplet sizes. Also, the filament or rods can overload causing centrifugal stripping. They can shatter large droplets on impact causing significant mass recovery errors. Another source of error is re-sampling of the same volume of air if the rotational speed is too high or the windspeed is too low.

The rotorod sampler is infrequently used. The handling and operational difficulties (constant rotational speed, overloading, resampling etc.) precludes its use in most spraying operations. However, if integrated mass or dosage information is needed, this sampler can be very useful because of its ability to eliminate most variable windspeed problems.

A small, simple and elegant sampler known as the flag sampler, developed by the US Forest Service, Missoula Equipment Development Center (MEDC), is included as a rotating sampler, admittedly, a very loose classification. The sampler is made of a spring wire shaft, fitted with a glass tube bearing which is inserted into a small wooden dowel. Two small pieces of Kromekote card are used with the spring wire shaft/dowel arrangement. One card is folded and glued to the spring wire shaft and serves as a flag and a means of turning the shaft with the wind. The second small Kromekote card, 0.125 inches wide by 1.5 inches long, is inserted into the spring wire clip at the top of the shaft and is the actual collector. In this way, the small sampler is always oriented into the wind and disturbs the airflow only minimally.

Suction

A more complex group of samplers are those that require the drawing of air into the sampler. One of the simplest suction samplers is a commercial filter pad sampler connected to a vacuum source. This sampler contains one thin cellulose, or glass felt porous membrane, 4.7 cm in diameter. The holder is plastic or metal, opened at one end, and terminates in a tube to which a vacuum hose is connected. The aspiration rate is 1 to 6 L/min. It works by impaction of the droplet on very fine fibers or it can work as a suction sieve, depending on the pore sizes of the filters. Although the filter itself is very efficient, several errors can be introduced at the inlet to the sampler. First, the sampler must be faced into the wind because mismatch of the sampler aspiration rate and the wind velocity often occurs and misorientation from the wind direction will cause undersampling of the large droplets. The error increases with an increase in the angle of orientation from the direction of wind flow. Second, even if it were possible to keep the sampler oriented into the wind, possible only in tests such as wind tunnel and chamber tests, the sampler presents an obstacle to the streamline flow which affects the droplet sizes collected. The sampler can also overload, especially if particulate matter is sampled, causing the filter pad to plug which lowers the flow rate.

The cascade sampler is another suction impactor which separates the droplets or particles into a series of size groups by passage of the airstream through a series of nozzles each of decreasing size. As the air stream passes through each nozzle, its velocity is increased thereby improving the efficiency of the impaction. The droplets impact on a stage or surface such as a microscope slide. The larger droplets (50–100 μm) impact on the first stage where the velocity is the lowest. The smaller droplets (2–10 μm) impact on the last stage where the velocity is the greatest. If the stages are not overloaded, the droplets may be counted. In addition, the analyte on each stage may be washed free and the mass determined if a sufficient quantity has been collected to allow measurement. However, evaporative loss is a problem even for liquids that have low vapor pressures (10^3 mm). Obviously a tracer must be added if the mass is to be determined. Thus, this type of sampler can give a droplet size estimate as well as an airborne mass determination at a specific sampling location within a spray area (or downwind). Unfortunately, overlapping size distribution, internal wall loss, aspiration variations, etc. complicate the interpretation of the results.

High volume samplers, capable of aspirating 20 to 50 ft ^{3}/min. are additional examples of suction samplers. These samplers use either soluble or non-soluble collection filters such as Gelman® and Millipore® filters of specific pore size. Their collection efficiency for particles as small as 0.01 μm is over 95 percent. These samplers can also be used for total mass analysis of tracer or other particulate materials. Because of the high volume, the operational sensitivity is increased if used where the spray concentration is very dilute such as in downwind drift areas. Some of these samplers are multistaged and separate the particle sizes on several successive stages. The Anderson Cascade Hi-Volume sampler® is an example of this type of sampler.

Efforts have been made to develop an isokinetic sampler. An isokinetic sampler is one that is operated at a flow rate such that the velocity at the sample entrance exactly matches the wind velocity and which is constantly oriented to face into the wind. However, an isokinetic sampler that tracks changes in wind velocity by changing the inlet diameter and orients itself into the wind at all times is not available. Typically, the flow is set to be isokinetic at some mid-range wind speed. To illustrate how this can adversely affect sampling accuracy: if the sampler's flowrate is set too high, undersampling of the large droplets occurs and the sampler acts as if it has a smaller sampling cross-section than it actually has. Also, the sampler presents an obstacle to the air flow and diverts the smaller droplets. Attempting to apply corrections for the inefficiency of isokinetic samplers is at best difficult.

Suction samplers all require a vacuum source. This means that a pump and a source of power must be available. Although some samplers such as Millipore® and Gelman® are quite small (approximately 4.7cm in diameter 15cm long) the pump and power sources needed to operate 10 or 15 of these samplers will weigh up to 100 pounds. The size and capacity of a pump needed to provide suction for a high volume sampler (20–50 ft^3) usually requires a field generator because of the current draw necessary to operate the motor. This means more weight, fuel, etc. In addition, some of these samplers are fairly expensive ($1000 to $6000). These factors definitely limit the number of samplers that may be used on experimental and forest spray operations.

Vapor Sampling

Spray operations result in the generation of chemical vapors in and downwind of the target area. The vapors evolve from the evaporation of the chemical of interest from the surface of droplets as they fall. Also, secondary vaporization results from the evaporation of the chemical from the surfaces of foliage, wood, ground, and even the sampler. In order to obtain adequate accountancy of the mass of chemical sprayed, that portion that is in the vapor state must be measured. This is usually accomplished through the use of bubblers or solid sorbent tubes that are placed at pre-selected locations.

A bubbler is a small glass cylinder that measures 15 to 20 cm in height by 2 to 3 cm in diameter. The intake is a small glass tube approximately 1 cm in diameter, sealed to the top of the cylinder and extends from the top of the cylinder to within a few mm above the bottom. The intake tube terminates in a small capillary opening at the bottom end. A small side arm tube is attached to the side of the cylinder near the top. The side arm is connected to a vacuum pump usually by a length of rubber tubing. The bubbler is partially filled with an appropriate solvent. The chemical vapor laden air is drawn into the inlet tube by the vacuum pump and passes through the capillary end forming air bubbles in the solvent. The size of the bubbles is regulated by the size of capillary end. The smaller the capillary opening, the smaller the size of the bubbles. The vapor in each air bubble is absorbed in the collecting fluid. Small bubbles are necessary for the solvent to efficiently "scrub" the chemical vapor from the air bubble. The bubble passes up through the solvent, causing considerable turbulence and mixing in the liquid. The scrubbed air then passes out of the bubbler through the side arm to the vacuum source.

The flow rate of air (aspiration rate) through the bubbler is controlled by a small flow limiting calibrated orifice, called a critical orifice, that is placed between the bubbler outlet and the vacuum source. Normally, the aspiration rate used with this type of bubbler is 1 L/min. The rate can be varied by changing the critical orifice. Often the air sampling rate is increased in order to sample a larger volume of air thereby increasing the mass of chemical dissolved in the collection solvent. This may be necessary to meet the detection requirements of the test and/or the sensitivity of the analytical method used to analyze the bubbler's content (the solvent volume can also be reduced to increase the concentration of the chemical of interest in the solvent). Care must be taken in changing the aspiration rate. If the flow is too high, solvent can be entrained in the air and pass into the vacuum source resulting in large errors in the results.

The bubbler configuration may be altered to improve the vapor collection efficiency and/or to permit the use of higher aspiration rates. One example is the glass bead bubbler. In this case, the bubbler is partially filled with small glass beads. The glass beads aid in the break-up of the air bubbles. This improves collection efficiency and permits the use of higher aspiration rates (6 to 12 L/min.). Another bubbler configuration is the "glass frit" bubbler. The use of a glass frit at the bottom of the bubbler inlet stem is another way the collection efficiency of a bubbler system can be improved. The glass frit breaks the incoming air into very fine bubbles and increases the surface area of the air that is scrubbed by the solvent. The aspiration rate cannot be increased significantly with this type of bubbler because the air break-up into very small bubbles causes the solvent to "froth" if the aspiration rate is too high (greater than 2 or 3 L/min.).

Bubblers can be used both within the target area and downwind. However the bubbler inlet must be protected from the aerosol droplets if the vapor and aerosol portion are to be accounted for separately. This is accomplished by placing small plastic rain bonnets on the top of the bubbler. In this configuration the air is drawn in from the underside of the bonnet before passing into the bubbler inlet, thereby eliminating sucking most aerosols into the bubbler solution.

The efficiency of the bubbler solvent to remove the chemical from the air bubbles must be determined. The initial consideration in selecting the collection solvent is the solubility of the chemical of interest in the solvent. The higher the solubility, the higher the collecting efficiency. However, the dissolved chemical may be volatilized or desorbed from the solvent. Thus, it is necessary to determine the collection efficiency of the bubbler/solvent combination to scrub the particular chemical vapor from the airstream. This must be done each time a new solvent or new bubbler configuration or different spray formulation is used.

Another problem associated with selection of collection solvents for a chemical is the stability of the spray formulation in the solvent. If the post spray analysis is delayed significantly, decomposition of the chemical of interest might occur.

Bubblers can be used with sequencing equipment in order to divide the total sampling time into smaller time increments rather than just total time integrated samples. Sequencers are equipment that follow a predetermined sequencing schedule or can be "switched" on demand if they are hardwired or radio controlled. Each tube is aspirated for a period of time and then the vacuum is applied to the next bubbler.

Finally, bubblers require a vacuum and a power source. Depending on the number of vacuum pumps and the capacity of each pump size, the power source (battery or generator) can vary significantly because of variable power requirements. The weight of the system can be a very limiting factor regarding the number of bubblers especially if sequencing equipment is used. A sequencer-pump-battery system we have used extensively weighs 125 to 200 pounds. However, this system is used with 10 to 20 bubblers, not just one. The cost of this system is $1500 to $3000 per station.

Bubblers are classic vapor samplers and have been used successfully on innumerable tests for many years. If care is exercised, the results obtained from bubbler samples are reliable and credible. Unfortunately, bubblers require the use of solvents, and they are fragile. Breakage can be a problem especially if they must be transported over rough terrain. It is unlikely that the analyses will be perfomed in the field so they must be transported back to laboratory. Surprisingly, they are not as expensive as might be expected. When mass produced (lots of over 1000 bubblers) they cost $5 to $6 each.

Solid sorbent tubes are used much the same as bubblers and give the same information. They are constructed of glass or stainless steel and vary in size, ranging from 2-3 cm in length and 1-2 mm in diameter (internal diameter) to 15 to 20 cm in length and 6 to 7 mm in diameter. The tubes are partially filled with a fine powdered sorbent material. A sorbent known as Tenax® is widely used. The mass of sorbent packed in the tubes varies from 5 to 10 mg in the smaller tubes to 100 to 150 mg in the larger tubes. The larger the mass of sorbent, the larger the load capacity of the tube (the amount of chemical vapor that can be sorbed by the solid sorbent before overloading occurs). The size of the tube also limits the aspiration rate. With the small tubes the aspiration rate is limited to about 20-50 mL/min while 0.5 to 1.0 L/min can be used with the large tubes.

After the solid sorbent tubes are used to sample chemical vapors, they are returned to a laboratory for analysis. The chemical vapors are removed from the solid sorbent tube either by elution with a solvent or by thermal desorption. If solvent elution is used the resultant solution can be analyzed by a number of analytical techniques (spectrophotometrically, gas chromatographically, liquid chromatographically, etc.). If thermal desorption is used the analysis usually is performed by gas chromatography.

Solid sorbent tubes offer several distinct advantages over bubblers. They are more durable and breakage is a small problem. They are smaller and don't require the handling of solvents or solvent filled samplers in the field. The sorbed vapors are usually more stable on the sorbent material than in solvents. Usually, an increase in overall detection sensitivity is realized by using solid sorbent tubes. But, they also require a vacuum and a power source. However, the vacuum pump that will suffice is much smaller than those regularly used with bubblers. As a result, a much smaller power source can be used (even if sequential sampling is performed). But, sophisticated laboratory support and expensive analytical instrumentation is needed to perform the analysis. The necessary technical support is higher. Finally, the use of solid sorbent tubes is less labor intensive than bubblers (they require less cleaning and do not have to be re-filled before each test). They are expensive, especially the tubes used with commercial automatic thermal desorption equipment. Unpacked tubes can cost $20 each. As mentioned before, an increase in sensitivity is often realized when solid sorbent tubes are used. However, this can be a mixed blessing, because solid sorbent tubes suffer from "memory effects". This occurs when all of the sorbed vapors from a previous test are not desorbed from a tube after extraction or thermal desorption. This results in erroneously high results when the tubes are used again and may cause confounding results.

COMPLEX AND SOPHISTICATED SAMPLING DEVICES

The equipment we have selected for inclusion in this section are under experimental development/evaluation or used only on selected spray operations. They are expensive, require technically trained personnel to operate and maintain them and may present unacceptable logistic problems. However, the advantages gained from their use is that the response generated by this equipment is usually "real-time" or "near-real-time". Although extensive data reduction may be required after completion of the chemical dissemination phase of the operation, the ability to "see" what is happening during the conduct of the spray mission is very valuable and results in a faster, more efficient completion of a program. In addition, the data is more refined. For example, the response is continuous as well as being in real-time and this produces an accurate measurement of the concentration versus time profile.

It is difficult to fix an accurate cost estimate to some of these devices because they are experimental and only one or two exist. Thus, the total engineering and development costs is all that is available. Even if subsequent models are fabricated the cost can still be very high ($50,000 to $500,000). Of course this is an extreme case, but is presented to illustrate the expense that attends this type of testing.

The devices discussed here are mostly point samplers. Only a few integrated line samplers are discussed. As with the commonly used devices, only those that have been used on select spray programs or that show considerable promise and provide more data than is possible with the commonly used equipment are included. Again, this is not all inclusive. The general types are listed in Table 3.

Chemical and Physical Detector/Samplers

The chemical and physical detectors are systems which detect and measure a reaction product (chemical) or those which measure directly the chemical of interest. The groupings are based upon those systems that have been developed for a specific application.

Photometric and Electrochemical

Very few of these instruments are available for use on spray programs. They have been developed for specific applications other than forest spray programs and would require considerable chemical and instrumental development before a judgment can be made as to their applicability to the needs of a forest manager. They are point samplers. Thus, a significant number would be needed or a complex multipoint sampling system would have to be developed to collect samples from a number of sampling locations in order to provide the necessary data for modeling purposes. However, the more extensive the sampling system or the more points sampled (by one detector) the longer the analysis time and the further away from real-time the response becomes. They are mostly used to sample vapors, but they might be adapted to aerosol measurements if an inlet vaporizer were developed.

The photometric systems must have a vacuum source in order to draw the sample into the sampler. A light sensing unit is used in conjunction with a reaction reagent that generates a specific product. These reaction products can be detected by absorbance (Fitch and Gargus 1985), or by fluorescence or chemiluminescences techniques (Gehauf and Goldenson 1957). These instruments use reagents, are moderately heavy (10 to 25 pounds for just the detection system), expensive ($8,000 and up) and would require considerable expertise to operate and maintain. The electrochemical systems use potentiometric measurement to quantify specific compounds. These samplers also use reagents and are expensive.

Gas Chromatography

Gas chromatography (GC) is one of the premier analytical techniques used in the laboratory today. Some versions have been reduced in size and weight and packaged for use in the field. They can be used with gas switching valves that incrementally sample the vapor laden air or they can be used with solid sorbent tubes. These instruments have found application primarily in the area of vapor sampling and would be useful in the downwind area. However, heated inlets are needed which convert aerosols into vapors before they will be of much value in the target area.

GC's are expensive ($8,000 to $15,000 for the instrument, data processing is extra) and are not simple to operate in the field. They have been miniaturized and lend themselves to mobile analysis. They have been attached to aircraft and used to sample downwind drift (Elias 1975). Considerable effort has also been expended to miniaturize and to speed up the GC analyses time (Saadat and Terry 1984). Progress in these areas and reduction in cost will govern the usage of GCs in future forest spray operations.

TABLE 3: Classification of Samplers

Sampling Classification		Instrumentation
Chemical and Physical Detection	1.	Photometric & Electrochemical
	2.	Gas Chromatography
	3.	Mass Spectrometry
	4.	Solid State
	5.	Emission
Optical	1.	Scattering
	2.	Absorption

Mass Spectrometry

Field mass spectrometers (MS) have been developed for detection and quantification of organic vapors in the environment. MS is a highly sensitive and specific detection system which relies on the ionization and separation of the compounds present in a vapor sample. The separation is obtained from the used of time of flight (ionic velocity) or magnetic field (quadrupole) techniques. They can be used with multiple point sampling systems in order to reduce the number of MS units needed. But, the cost of one MS is very expensive ($50,000 and up). Claims have been made that MS samplers have been simplified and greatly reduced in cost and are fieldable (Meier 1978). However, specificity and sensitivity often are degraded when sophisticated techniques are simplified or reduced in size.

A variation of mass spectrometry is ion mobility spectrometry, (IMS) or plasma chromatography. IMS analyses are performed at atmospheric pressure. A radioactive source, such as Ni-63, produces reactant ions. The molecules of the compound of interest exist as vapors and undergo a reactant ion/molecule reaction which generates product ions. The specificity of this technique is obtained from the type of ion/molecule reaction and the different velocities to give the product ions as they travel in an electric field toward an ion collector. This technique is reputed to be sensitive in the sub part-per-billion range and could be used to monitor vapors. A small IMS system that may be suitable for field use is described by Spangler and Carrico 1984 and Carrico, et al. 1986. The cost is unknown.

Solid State

Considerable research has gone into the development of piezoelectric crystal sensors. The piezoelectric crystal is the frequency regulator in an oscillator circuit. They can be used in the oscillator mode or as a surface acoustic wave generator. Specificity for a particular chemical is obtained through the use of a chemical coating that is placed on the crystal which has a high degree of solubility for a specific class of chemical compounds. Specificity is also obtained from an array of crystals, all placed in one sensor head, each coated with a different compound. These devices operate in the sub-part-per-million to the part-per-million range (Guilbault and Jordan 1984, Jarvis et al. 1986, Olness et al. 1986). They are used to measure vapors. It is possible that they may be made applicable to aerosol sampling if the appropriate vaporization inlet can be developed. These devices are not commercially available and considerable work is needed before they can be used in the field. The cost may be high.

Emission

A commercially available emission detector known as a flame photometric detector (FPD) has been used extensively by many monitoring and testing agencies such as the US Environmental Protection Agency, the Occupational Safety and Health Administration, the US Department of Defense, and a number of organizations within the Canadian Government. The instrument is presently manufactured by Columbia Scientific, Austin, Texas. This device has a high degree of specificity for phosphorus and sulfur bearing compounds. The selection of either phosphorus or sulfur is done by a change of light filters. The detector has been packaged for use in the field and chambers as well as the laboratory. The basic unit has often been modified to fit certain test or monitoring requirements. Although it is very sensitive (0.005 μg/L) it can only be used to quantitate vapors. Heated inlets have been moderately useful. It requires power, hydrogen gas, is moderately heavy (20–30 pounds) and costs $14,000. It can be multiplexed to sample a number of locations in sequence but this suffers from all the problems of multiplexing previously mentioned. A few of these detectors judiciously positioned can provide vast amounts of data.

A small atomic absorption spectrometer (the absorption is obtained after excitation) has been developed that can be used in the field to quantitate metallic particles (Comeford 1987). The particles must be very small in order to be aspirated effectively into the burner assembly. The unit has not been packaged for field use but has been used in chamber tests and may be useful to measure metal tracers used in forest spray operations. Unfortunately cost, logistic, and technical expertise required are prohibitive at this time.

Optical

Both scattering and absorption will be considered together in this paper because an overlap in operation exists between some of the instrumentation that is included in this section.

A very effective, commercially available point vapor sampler known as a MIRAN® has been successfully used on many test programs at Dugway. This is a long path, miniature infra-red gas analyzer manufactured by the Foxboro Company, Foxboro, Massachusetts. A high degree of specificity can be obtained from a grating filter wheel that can be adjusted to a specific wavelength that is characteristic of a class of organic compounds (acids, aldehydes, alcohols, etc.). The sensitivity is dependent upon the pathlength of the cell. If operated at the maximum pathlength (20.25 meters) the sensitivity of some MIRAN® models is from the sub part-per-million to the part-per-million range. The signal output is compatible with most digital data reduction equipment.

The MIRANs® require a power source and are moderately heavy (10–40 pounds). They are expensive, $7,000 to $14,000, depending on the model selected (data reduction equipment is extra). They are used to measure vapor concentrations. Again, they may be adapted to aerosol sampling if vaporization techniques are developed.

Backscatter lidar (light detection and ranging) is the most commonly used of the lidar systems. The system uses a high power, non-tunable laser to detect changes in density of the atmosphere caused by aerosols. Backscatter lidars have been used to track smoke plumes, dense clouds, etc. in the atmosphere (Carswell, 1983). These devices are very expensive ($50,000 and up) and require a high degree of technical expertise to operate. They are considered mobile but this must be qualified to the extent that they must be mounted in a substantial carrier (van, aircraft, etc.).

The concentration of vapors in the atmosphere can be determined by differential absorption lidars (DIAL). Two or more light wavelengths are used, either by varying the frequency of the laser or by using two lasers, each at a fixed, but different frequency. The difference in absorption between a wavelength of light that is absorbed by molecular species present in the atmosphere compared to a wavelength that is not absorbed is how the DIAL systems operate. The attenuation of the non-absorbing wavelength is due to scattering by constituents in the atmosphere other than the chemical of interest and these data are used to correct the analytical wavelength for scattering loss to yield absorption results. Many different chemical species have been studied using the DIAL technique. The DIAL measurements can be either path-averaged or range-resolved.

The path-average DIAL measurements use backscatter signals from reflectors (natural targets or mirrors) to measure the content of a chemical species in a light path. An example of this type of measurement has been described by Killinger et al. (1980) in which carbon monoxide emitted by automobiles was measured at a range of 500 meters. The concentration ranged from the parts-per-billion to the parts-per-million. Unfortunately, concentration versus distance information could not be obtained from this type of arrangement. Recent tests have shown if partially reflecting targets spaced across the path traversed by the laser beam and the return signals from each partial reflector measured, the resultant data will generate a three-dimensional map.

The range-resolved system produces a continuous signal from the backscatter of atmospheric aerosols as a function of range. High powered lasers must be used to gain sufficient sensitivity.

These systems are complex, expensive and do not readily lend themselves to spray operations. They are experimental and are most effective when used at test locations that are free of trees, mountains, etc.

CONCLUSIONS

Some of the experimental systems show considerable promise, especially the DIAL systems. But the expense of each unit and complexity of operation will limit their application. It is doubtful that a forest manager will be able to afford such equipment on regular spraying operations. It is possible that a few of these instruments could be used on many individual spraying programs if they were located and available at a central laboratory that provided field support to the operational side of the Forest Service. This would amortize the cost of the units over many spray programs. Still, the cost of the technical personnel would be high. It all revolves around cost.

The simple, commonly used samplers (sedimentation, impaction, etc.) will continue to be the samplers of choice. Obviously, cost and ease of use are the determining factors. They provide reliable data if the limitations of each are recognized. If the delivery system and aircraft are well characterized, quantification of sprayed pesticides, herbicides, etc. within and downwind of the target area are achievable with these devices.

Many spray operations need little more than visual marking of the aerosol cloud travel and/or droplet deposition. Other programs require mass recovery and droplet sizing. The samplers currently used are adequate if the strengths and limitations of each are recognized and the data treated accordingly. Cloud drift is an area where sampling capabilities are limited and is the area where instrumentation such as backscatter LIDAR and DIAL systems will provide the greatest benefits.

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QUANTIFICATION OF SPRAY DEPOSIT IN EXPERIMENTAL AND OPERATIONAL AERIAL SPRAYING OPERATIONS

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ABSTRACT — Use of Kromekote^{UM} cards on the ground were progressively replaced by natural needles collected in the canopy to evaluate spray deposit. Contrary to 10 × 10 cm cards, needles intercepted the same droplet size and number as the target the spruce budworm larva. For calibration, where many trials are repeated on the same area, synthetic needles were conceived to replace natural foliage. With the number of drops per needle, we can predict foliage protection and in some cases, survival population reduction.

The deposit assessment method used in Quebec during operational spray programs against spruce budworm is presented. Also we review studies conducted by researchers of New-Brunswick on the same subject. Finally, a complementary method, the proteinic dosage, is presently tested to get a new tool allowing us to improve our results.

RÉSUMÉ — L'utilisation du papier Kromekote^{MD} 10 × 10 cm placé au sol a été progressivement remplacée par la récolte d'aiguilles naturelles dans la cîme des arbres pour évaluer le dépôt d'insecticide. Celles-ci s'avèrent un capteur plus fidèle du nombre et de la dimension des gouttelettes retrouvées sur la cible, soit la larve de la tordeuse des bourgeons de l'épinette. Pour le calibrage, où l'on répète plusieurs traitements sur une même superficie, des aiguilles artificielles ont été conçues pour remplacer le feuillage naturel. Avec le nombre de gouttelettes par aiguille, nous pouvons prédire la protection accordée au feuillage et dans certains cas, la réduction de survie de la population larvaire.

La méthode d'évaluation du dépôt utilisée au Québec durant les programmes opérationnels contre la tordeuse des bourgeons de l'épinette est présentée. On résume également les études menées par les chercheurs du Nouveau-Brunswick sur le même sujet. Enfin, une méthode complémentaire, le dosage protéinique, est présentement à l'étude afin d'augmenter la précision de nos résultats.

GENERAL

When a spray cloud is observed from the air, it is possible to ascertain whether it extends to, and penetrates well inside, the canopy; the spraying can then be presumed to have been successful.

However, when the purpose is to quantify the insecticide present in order to measure its impact on the intended objective, a more complex exercise than a simple visualization is required.

The distribution of the deposit inside the canopy is generally highly heterogeneous; several factors are behind this, such as local weather conditions, topography, forest roads, tree density, defoliation, etc.

According to Maksymiuk (1963), the filtrating effect of a tree stand is felt over a distance equivalent to three times the height of the trees forming that stand. In assessing the insecticide deposit on a Kromekote card placed on the ground along a forest road, this filtrating effect cannot be ignored. Furthermore, it has been shown on several occasions (Ekblad, 1978, Fast et al., 1984, Lambert 1985) that this collector does not intercept the same droplet spectrum as coniferous foliage and defoliating insect larvae. Droplets collected on the ground are generally larger (Barry *et al.* 1977) and less numerous (Snowden *et al.* 1977). According to Himel and Moore (1967), 93% of droplets reaching eastern spruce budworm larvae have a diameter under 50 μ. For their part, Barry and Ekblad (1978) conclude that the droplets found on conifer needles have a diameter under 70 μ. On the other hand, Wiesner (1984) and Sundaram *et al.* (1985) claim that assessing deposits on Kromekote cards is an inadequate measurement of what is found on the actual target, that is, pest habitat foliage. Wiesner (1984) adds that small-sized droplets are not only effective, but there are strong possibilities that they are largely responsible for larval mortality. Consequently, an adequate method for quantifying deposits had to be developed.

INTRODUCTION

Guided by new knowledge, the Service de la protection contre les insectes et les maladies (SPIM) of Quebec's ministère de l'Énergie et des Ressources (MÉR) has made a number of changes in its spraying operations. Spraying systems were replaced and gauged so as to deliver droplets between 25 and 80 μ after evaporation, and a method for assessing deposits was developed.

One of the priorities of the SPIM's Spray Technology Division is to ensure maximum effectiveness of the insecticide and maximum productivity of the spraying airplanes while minimizing impacts on the environment. Studies were conducted in 1984 to determine the minimum quantity of insecticide required on the needles of balsam fir, *Abies balsamea* (L.) Mill in order to create a discernable negative effect on eastern spruce budworm survival, *Choristoneura fumiferana* (Clem.) after an operational spraying.

The method used had to be suitable for assessing deposits at the time of operational sprayings, and for gauging the spraying systems. A second objective was to link larval mortality and annual defoliation to the insecticide deposits on fir needles.

This article describes the sampling methods used in Quebec in assessing insecticide deposits. Practical application of these methods is also demonstrated and the findings of certain other researchers are reviewed in order to complete our knowledge on the subject.

MATERIALS AND METHODS

One hundred and fifty-two (152) sample trees were treated with Fenitrothion[1], in two sprayings, at 3 to 5-day intervals, on the basis of a 210 g/ha dosage and a final volume of 1.403 ℓ/ha. One hundred and fourteen (114) sample trees underwent a single biological treatment made of pure Thuricide 48LV™[2], applied at the rate of 30 BIU/ha in a final volume of 2.37 ℓ/ha. Only the chemical insecticide contained a dye, but it was not fluorescent.

Two types of single engine aircraft were used: a Bull Thrush and an Ag-Cat 600G; they were gauged to produce the same droplet spectrum. The spraying system consisted of six Micronair AU5000 with flowmeter and 9cm blades at 35°. Spraying took place from May 29 to July 1, 1986, early in the morning or at the end of the day. Data used for droplet spectrum and relationships between natural and artificial twigs were collected in 1985.

Sample trees were selected by groups of five from within the spraying blocks, specifically in young fir stands where tree heights rarely exceeded 10 m.

The effect of spraying attributable to the insecticide (Abbott, 1925) is expressed in two different ways and calculated as follows:

Reduction in survival (%):

$$1 - \left[\left(\frac{\text{postspray treated}}{\text{prespray treated}}\right) \times \left(\frac{\text{prespray control}}{\text{postspray control}}\right)\right] \times 100$$

Foliage protection (%):

$$\left[\frac{\text{defoliation control} - \text{defoliation treated}}{\text{defoliation control}}\right] \times 100$$

Prespray and postspray assessments were made on 45 cm branches selected among the sample trees. Defoliation was determined using the method described by Fettes (1950) on the branch used for the postspray.

On each sample tree, eight twigs were collected at random on a branch in the upper mid crown. The maximum deposit can be measured at that level (Barry *et al.* 1981). Twigs were placed individually in jars designed in such a way that no contact with the needles was possible. The jars were transported in coolers and placed in a refrigerator pending examination of the needles. The number of samples taken was based on the manpower available at the time the needles were collected after spraying.

Twenty needles per twig were placed on a slide covered with rubber cement, 10 on the bottom face and 10 more on the top face. Droplets were generally counted on the needles of previous year foliage. Current year twig foliage was used when the twigs were completely spread out. According to Fast *et al.* (1984), there is no real difference between assessments of the deposits on the needle and assessments of those on the buds as regards treatment efficacy. The correlation between these two types of collectors is 0.789.

The droplets were counted and sized using a Wild M420[1] microscope and two fibre optic swan-neck and ring illuminators[2] fed by two Intralux 6000[3] units. The magnification used for counting droplets on the natural foliage was 40×, and a graduated reticle inside one of the eyepieces made it possible to measure the size of the droplets.

Biological insecticide deposits were also assessed on aluminum targets cut out in the shape of a needle (Figure 1). The artificial twigs were raised in parallel to the branches of the sample trees, that is, to the level of the upper mid crown, using a telescopic pole equipped with a clip. Using the equipment described above, five needles were counted on both faces of each twig.

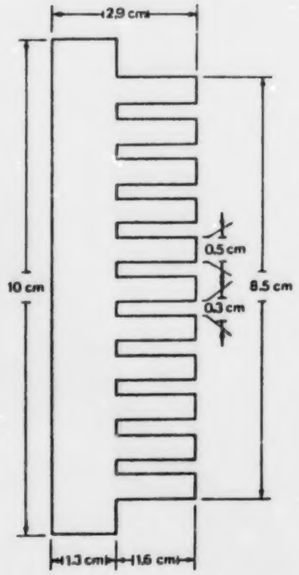

FIGURE 1: MODEL OF ARTIFICIAL TWIG.

The spread factor was measured for each of the products (Table 1), using Dr. A. Sundaram's modified method (Bergeron, 1985). Droplet sizes expressed by the NMD (number median diameter) thus allowed the real size of droplets found on the fir foliage to be determined.

Weather conditions registered during sprayings can be summarized as follows: very stable inversion conditions at the crown level, very high humidity rating (85% average), low temperatures (5°C average) and winds not exceeding 10 km/hr. The details of this information are available in a report by Lambert and Barras, 1987.

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(1) Fenitrothion: Sumithion™ is a registered trademark of Sumitomo Chemical Ltd.

(2) Bacillus thuringiensis Var. Kurstaki: Thuricide 48LV™ is a registered trademark of Sandoz Inc.

(1, 2, 3) These microscopic instruments are sold exclusively by Wild Leitz Canada Ltd.

TABLE 1: Spread factor equations used to correct diameter of stains.

Insecticide	Collector	Equation	r^2
Thuricide 48LV	Natural needle	$Y=28{,}283 + 0{,}149X + 0{,}00025X^2$	0,986
	Aluminium card	$Y=4{,}030X^{0{,}493}\,(1{,}001)^x$	0,948
Fénitrothion	Natural needle	$Y=2{,}152+0{,}656X$	0,879

Finally, the data were grouped by 0.10 drp/needle deposit class and associated to the corresponding measures of efficacy. The empirical model, which can be adjusted to the various relations studied and which explains them mathematically and biologically, is the following:

$$Y = B_0+B_1\,(1\text{-}e^{-B_2x})$$

Where Y = (protection given the foliage and reduction in the survival rate);

X = insecticide deposit found on the foliage (nb. drp/needle)

B_0 = 0, the model must intercept the x and y axes at (0,0) since the absence of insecticide does not generate any efficacy;

B_1 = $\leq$ 100, the asymptote is at 100% since it is logically impossible to obtain a higher response.

Biologically, this equation expresses the fact a very minor addition of insecticide can double the protection given to the foliage. However, there is a point where an increase produces no additional response.

The goodness of fit of this model is calculated through the coefficient of determination (R^2).

RESULTS

The droplet spectra for tests as a whole are shown in Figure 2. Ninety-one percent (91%) of the droplets detected on the fir needles had a diameter equal to or under 68 μ. All droplets had a diameter under 128 μ.

Table 2 summarizes the statistical analysis of the data. The value of the parameters is indicated for each efficacy-deposit relation according to the type of insecticide. Based on coefficients of determination, the mathematical model used explains respectively 69%, 93%, 5%, 63% and 92% of observed variations according to relations 1 to 5, respectively.

Figures 3, 4, 5 and 6 represent these relations in graphic form. Based on:

(a) the mathematical model used;

(b) the data collected in the summer of 1986;

(c) the 19.1 ± 11.1 (Fenitrothion) and 18.5 ± 14.9 (Thuricide 48LV) average PRESPRAY larval population.

We can state with confidence limits of 95%:

(1) that a 0.75 drp/needle average Fenitrothion deposit provides between 65% and 85% foliage protection and between 60% and 90% larval population reduction;

(2) that an increase in deposit to 1.15 drp/needle is required to obtain between 45% and 90% protection using a single application of Thuricide 48LV.

These intervals show that the efficacy of biological treatments is more difficult to measure than that of chemical treatments.

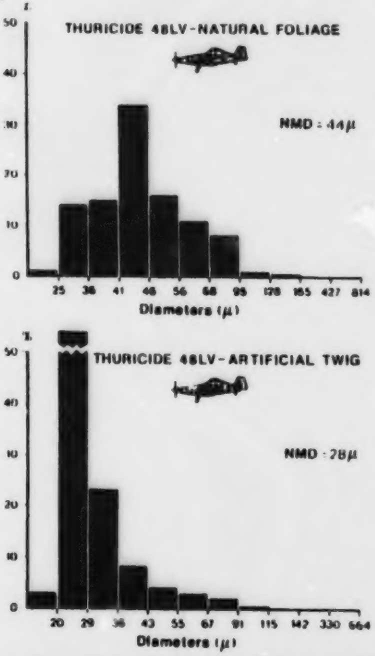

FIGURE 2: DISTRIBUTION BY % OF DROPS FOUND ON ARTIFICIAL AND NATURAL NEEDLES.

TABLE 2: Statistical analysis results in accordance with model $Y = B_0 + B_1\,(1 - e^{-B_2x})$

Relation	Insecticide	Parameters values	Coefficient of determination (R^2)
1. Reduction(1) vs Deposit(2)	Fénitrothion	$B_0 =$ 0,000 $B_1 =$ 100,000 $B_2 =$ 1,919	0,692
2. Protection(3) vs Deposit	Fénitrothion	$B_0 =$ 0,000 $B_1 =$ 100,000 $B_2 =$ 1,775	0,928
3. Reduction vs Deposit	Thuricide 48LV	$B_0 =$ 0,000 $B_1 =$ 49,597 $B_2 =$ 25,306	0,053
4. Protection vs Deposit	Thuricide 48LV	$B_0 =$ 0,000 $B_1 =$ 77,083 $B_2 =$ 2,892	0,627
5. Protection vs Deposit	Fénitrothion and Thuricide 48LV	$B_0 =$ 0,000 $B_1 =$ 99,816 $B_2 =$ 1,849	0,918

(1) Reduction in survival (%)

(2) Insecticide deposit on fir needle (drops/needle)

(3) Foliage protection (%)

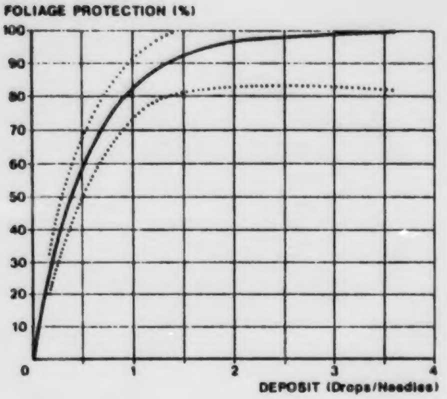

FIGURE 3: RELATION BETWEEN FOLIAGE PROTECTION AND DEPOSIT (FENITROTHION)

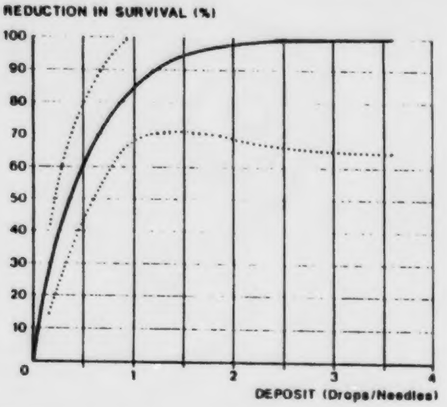

FIGURE 4: RELATION BETWEEN REDUCTION IN SURVIVAL AND DEPOSIT (FENITROTHION)

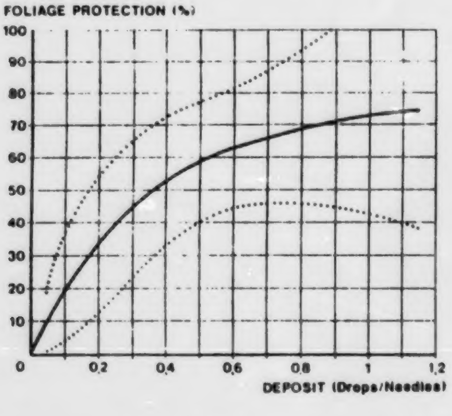

FIGURE 5: RELATION BETWEEN FOLIAGE PROTECTION AND DEPOSIT (THURICIDE 48LV)

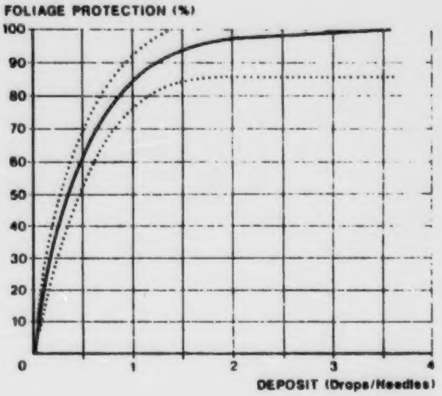

FIGURE 6: RELATION BETWEEN FOLIAGE PROTECTION AND DEPOSIT (FENITROTHION AND THURICIDE 48LV)

The relation between natural foliage and the artificial twig as an alternative method is very strong, with a coefficient of determination (R^2) of 0.89: $F=0.083 + 0.048PA + 0.002PA^2$ (Figure 7). Thus, 10 drps/needle on the twig corresponds to 0.8 drp/needle on natural foliage. For calibration, we recommend a threshold of 12 droplets/artificial needle to obtain optimum coverage. This exercise counted 25 samples treated with Thuricide 48LV and sprayed using a Bull Thrush equipped with 6 Micronair AU5000.

BRIEF DESCRIPTION OF A SIMILAR STUDY CONDUCTED BY THE NEW BRUNSWICK SPRAY EFFICACY RESEARCH GROUP (NBSERG)

In 1983, the NBSERG was mandated to establish a relationship between foliage deposits and the efficacy of on-site treatments. Sampling and data analysis techniques were developed. Up to 1986, various biological insecticides, such as Novabac, Thuricide and Dipel, were tested at various concentrations and dosages.

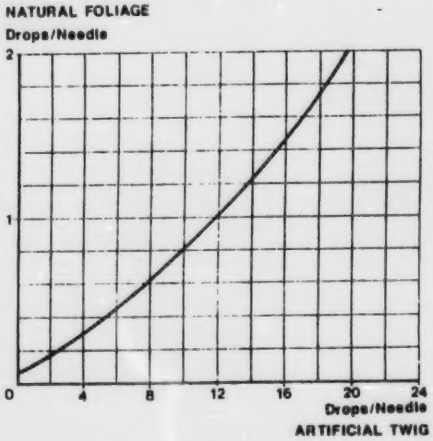

FIGURE 7: RELATION BETWEEN NATURAL AND ARTIFICIAL NEEDLES.

The techniques used for sampling and assessing insecticide deposits on foliage were developed by C.J. Wiesner (1982). These methods are identical to ours except for a few differences. In this particular case, the collected twigs are fixed by the branch to a sheet of styrofoam with enough room for about 20 twigs. The sheets are stored in cardboard boxes designed so they can be transported from the site to the laboratory.

Ten needles per twig are placed between two glass slides and the droplets are counted on both faces. The insecticide contains a compatible dye to facilitate microscopic analysis.

Defoliation reduction and larval survival are calculated by comparing the defoliation and mortality levels of each sample tree with that of untreated reference trees having the same prespray populations (Abbott, 1925). On the basis of the latter results, expected values are estimated and used to measure efficacy (Dorais and Kettela, 1982);

% efficacy = [(expected value — observed value) / expected value] × 100

The defoliation % is also used in relation with the deposit. Afterwards, the deposit values (nb. drp/needle) are transposed in logarithmic form to produce a linear relation and facilitate statistical analysis.

The first objective was to compare different B.t. potencies. However they have also remarked (Fast *et al.*, 1985) that 48LV gave marked reduction in survival as well as foliage saved, even at low deposit levels (0,5 drop/needle). This method is similar to the one developed in Quebec. Both can offer us good confidence in determining the efficacy of any kind of insecticide.

FUTURE PROSPECTS

Our next step will be to link the insecticide potential to deposit and to measures of efficacy. This information is necessary to optimize insecticide quantity to apply, to reduce volume and/or potency, therefore, to reduce operational costs.

In New Brunswick, Wiesner and Thomas (1987)[1] found a strong relationship between percent feeding inhibition and B.t. concentrations on fir foliage. Samples are washed and washes are incorporated into diet. Bioassays are carried out to determine the insecticide potential of the sample. Percent feeding inhibition is determined by comparing frass production from treated larvae as compared to a control (FRASS, bioassay method). Finally, feeding inhibition is correlated with the deposit measured by the visual technique (drops per needle) and with reduction in defoliation.

In Quebec we are studying the possibility of using the ELISA method for the same purpose. Many dilutions of samples are introduced in a sensitized carrier surface to B.t. toxic protein (antigen). An enzyme labelled antiglobulin attaches to the antigen. The antigen is detected by the enzyme label, changing the color of an added substrate. The optical density of the final color is directly proportional to the amount of unknown antigen in the original test solution. Relations can then be established with the desired parameters.

The advantage of this method is that it requires no bioassays; furthermore it would be possible to conduct directly on the site, establishment of insecticide potency on fir foliage.

CONCLUSIONS

There are now procedures for assessing insecticide deposits on balsam fir needles during operational sprayings. Moreover, raised artificial twigs are replacing Kromekote paper on the ground in gauging programs.

Results obtained in the last two years show that, with a given prespray population of 20 larvae per branch, an average deposit of 1 droplet per needle of fenitrothion provides effective protection of the fir foliage and reduction in survival (85% in both cases). On the other hand, the maximum protection achieved with Thuricide 48LV is 75% with 1.15 drops per needle. In both cases, 50% of the droplets had a diameter between 27 μ and 48 μ. Management specialists can consider a few options for improving these results, such as increasing the potency, carrying out two sprayings or increasing the dosage. Kettela (1986) has shown that an increase in dosage (64 BIU/gal) produces a significant increase in the degree of efficacy (defoliation reduction), especially at low deposit levels (< 1.5 drp/needle).

The percentage of protection given the foliage appears to produce a better estimate of the efficacy of sprayings than that provided by the percentage of survival rate. The latter rate can be affected by several variables other than the type of insecticide, such as predation, parasitism, disease, etc.

Whatever the defoliating pest, the product used, the canopy infested may be, it is essential to be able to determine the efficacy of sprayings on the basis of insecticide deposits. Since foliage is the very habitat of larvae in their destructive phase, quantifying the deposit directly on the foliage is the method that appears to be the most adequate.

When the quantity of deposit and the size of the droplets ensuring spraying efficacy are known, we are then in a position to adjust our systems to obtain the desired effect. However, the easily influenced interactions between the airplane and the target, such as the vortex, weather factors, evaporation, etc., will always have to be taken into account.

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SESSION IV DISCUSSION PERIOD

Panel Chairman — J.W. Barry
Panel Members — W.E. Yates, M. Houle, Marie-Claude Lambert

Jules Picot:

Well what I wanted to say was these papers were very interesting, especially those by Wes Yates and Marie-Claude *(Lambert)*. I just wanted to mention that there are two posters which reinforce those papers. Poster 7 which actually is a comparison of various types of aerial sprayers which are potentially useful in spraying coniferous forests for budworm control and you can see a comparison of the .... (inaudible) .... and Poster 4 on the question of measuring canopy deposit. I think you will find also that this is an interesting support to what Marie-Claude *(Lambert)* has to say that using the methods developed in New Brunswick 4 or 5 years ago based on a slightly different .... (inaudible). *(Dr. Picot had more to say on this subject but, unfortunately, the tape failed to pick up the remainder of his comments.)*

Steve Parkin:

I would like to ask Wes Yates a question. It's a question and a statement. We've been looking at the different measurement techniques with lasers and we've been looking in particular at the Malvern. This is in the UK .... in general people in the UK have been looking at the Malvern and the PMS system and making comparisons. I was very interested to see the ASTM sequence of round robin experiments that are being carried out that he reported. One thing that occurred to me was that the big link that appears to be between the systems is that one is a spatial sampler and one is a temporal sampler and the link between the two is that velocity is the key. If the velocity of the droplets is always the same then the spatial and temporal samples, in fact, are identical. I assume in the ASTM system, like we were carrying out in England, we were actually spraying in a stationary situation so we have a gradient of velocity because the droplets, particularly from a hydraulic nozzle, move at different velocities out of the nozzle and if so I was just wondering if anybody had actually tried to calculate back from using PMS 2D data where you can actually measure the velocity in the 2D probe ....you can get not only numbers and drop sizes but you can actually get velocity as well .... to try and see if you could actually get the same spectrum from a temporal sampler from a 2D and calculate the spatial and then compare that with the Malvern which is a spatial sampler. We actually did this. I have to say the answers were not all that encouraging in our instance and that we still had unresolved differences, so we consider it to not be just strictly the difference between spatial and temporal sampling. But I wonder if in that comparison you found anything different or if anyone actually bothered to back calculate as it went on to the spatial sampler?

Wes Yates:

Yes, you are exactly right, that was done in the study. I wasn't able to take time to report all the details but there was an attempt to convert some of the temporal results over into spatial on the basis of the velocity measurements that were done in the test and that only partially accounts for the differences between the instruments. A relatively small difference, but there was some difference because it was a static test as you suggested. The one I was discussing in the ASTM was a static test, and therefore the larger particles were going faster than the smaller ones, but that did not entirely account for the differences in the Malvern results compared with the other results.

Steve Parkin:

That's useful because we found exactly the same. It's good that independently we got the same sort of results. We might talk to you later about that.

Charles Wiesner:

I'd just like to make a short comment perhaps on Marie-Claude's *(Lambert)* presentation with respect to *B.t.* I'd hate to have people left with the notion that if you go beyond one drop per needle with 48LV that you are not getting anymore benefit from the application. I think that when we first started developing this technique of establishing dose response relationships in the field in about 1983 we found, as Marie-Claude *(Lambert)* has since then, that there is very definitely a logarithmic dose response relationship. Since that time we've looked at a number of formulations and formulations of different potencies and I think that the problem is not that you're not getting additional efficacy above one drop per needle but because of the logarithmic relationship, the incremental advantage is smaller obviously at the high end and also you are seeing that deposits that are very much above one drop per needle are fairly rare. I mean we've seen deposits with high potency *B.t.* applications up to 12 drops per needle, but numerically there are far less frequent deposits of that sort than the lower ones so that the combination of those two factors I think when you put them together tends to muddy up the data quite a bit at the high end. So I would think very definitely that we are getting increased benefit in efficacy at those higher levels.

Marie-Claude Lambert:

Thank you very much for this specification.

Chandra Nigam:

I am going to do a little bit of devil's advocacy here. What I am finding in my budworm behavior is that the budworm does not live or feed on old needles. It lives mostly on new needles. The correlation which is being established here with the old needles is more or less the same as the correlation you established with Kromekote cards. The behavior of budworm where it lives and feeds during the time of the spray is totally different. If you want to know how it is being killed, how the dose transfer is done, you have to see Poster 6 and there you will find how it is taking place and what is happening there. A lot of fine droplets in emulsion EC formulation, varying from 10 to 15 micron droplets are going into the budworm microhabitat. In ULV application which is not evaporating droplets from 15 to 25 microns, they are going into the budworm microhabitat. Thank you very much.

Unidentified Speaker:

That's a tough act to follow, but I just wanted to comment. Mr. Houle, I was interested when you mentioned that you thought solid sorbates were the more stable with regard to retaining the integrity of the chemical collected. I haven't worked with the impingers very much but I do know we ran into a problem with Matacil deteriorating on the solid sorbate, so I don't think we should put an over amount of faith in these solid sorbates.

This deterioration by the way is not due to breakthrough it was actually loss due to continued sampling of clean air.

Martin Houle:

Are you talking about the deterioration of the solid sorbate itself or materials sorbed on the solid sorbate?

Unidentified Speaker:

Of the material sorbed on the solid sorbate. In this case it was Matacil or aminocarb and we found continued drawing of air on this collected Matacil decomposed or just made the darn stuff disappear.

Martin Houle:

OK, what's been our experience is that in the time that is necessary to sample the air during the spray program, yes you draw in air and then we have stored these things — Porasil, Chromasorb, Tenax. Tenax is what we use the most and we have found that if we stored them at room temperature, ... (inaudible) . . . . that we did not in the long haul of say 2 weeks we did not see a deterioration of an analyte such as dimethyl methyl phosphonate, dimethylmalonate — these type of things. We did find that we would have some deterioration of the solid sorbate — it was more a function of the temperature of the desorption of the material if we used an automatic thermal desorber. Now that's not to say that there isn't going to be some type of problem that you may run into, but in our experience with what we have tested — and we have also collected some of the nerve agents — that we find that there is an increased stability of these various analytes as compared to the solution stability and, if you take many of these phosphonates, phosphonothiolates and the like, you will find that in normal collecting solvents like isopropyl alcohol, isoamyl alcohol, hexylyne glycol if you aspirate in the air and you get any water it would be interesting to see if you had the same stability that you obtained from the solid sorbate but you have to check out each system — I can't generalize and I shouldn't.

Wes Yates:

Basically, Martin *(Houle)* you check each of your materials by running blanks on them.

Martin Houle:

Yes, we'll put up a generator and aspirate for a predetermined period of time and then make various changes in the environmental condition such as relative humidity, temperature, and the like.

Alam Sundaram:

To add to the complexity of the situation of measuring droplets on the actual target as Dr. Nigam has pointed out the situation is really complex. We have done at FPMI cooperative research between our toxicology experts especially with Dr. Blair Helson, myself, and the chemical accountability section. The three of us got together and did a cooperative research and we found the droplets on nearly all the mature needles are significantly lower than droplets on new buds and because the buds were developing on a unit surface area basis we are not able to tell you exactly how many times higher but definitely at least 2–3 times higher number of droplets on the buds compared with the mature needles. I thought I better mention this aspect. Second, I have a question to Marie-Claude *(Lambert)* and that is, I am very much intrigued by the statement, at least I thought that's what she made, is the real target at least seemed to collect much lower number of droplets compared to the simulators — am I right?

OK

The similar behavior we also found. Definitely the simulators appeared to collect more droplets so we assumed probably we are not visualizing the droplets on needles so we thought why don't we extract and find out whether there will be difference in the active ingredient because, in spite of the fact that you might not be able to see the droplet the passive, active ingredient must be there. So we did the chemical analyses and we still found a significantly higher amount of active ingredient on the simulator as compared to the real biological target and this is a puzzle for all of us. Yesterday, Dr. Payne pointed out that electrostatic forces should not have that much effect especially when the droplets are not charged but I am just posing a question to the audience and those who would be interested in exploring this further it would be a very valuable information for everyone of us.

Unidentified Speaker:

We did this with plastic weeds. Had more problems with the plastic weeds than we had with the real weeds. The answer when we looked at it in the wind tunnel was pretty obvious. The plastic weed was not flexible in the wind the way the real weed was . . . . (inaudible) . . . . and it was quite obvious why the plastic replicate of simulated weed wasn't . . . .(inaudible) . . . . the real material.

Don Johnstone:

Mr. Houle mentioned in the use of . . . . (inaudible) . . . . samplers and particularly the rotorod type of device. In the work we have been doing with aerosols in Central Africa we have used a modification of the rotorod which involves using cutdown microscope slides, about 6 mm wide, coated with magnesium oxide as a basic sampler. What we are aiming to get from this is a measure of the droplet availability, that is the flux of droplets through a unique area, through the canopy and the air above the ground. We have found we can get what we believe is quite a reliable measure of this property, but we have to correct the data we take from the slides. The raw data from the slide is not a good measure of droplet availability. One has to correct for the lack of isokinetic sampling. The fact that the sampler is sampling at a different rate and at different wind speeds so one needs to correct to get the true sampling rate. One also needs to correct for the fact that the collection efficiency varies with droplet size and so we have carried out wind tunnel calibration of this rotary device to ascertain the collection efficiency at each droplet size class that we are counting so that having got the initial number counts in the range of size classes we can multiply up the numbers in the appropriate size classes in relation to collection efficiency to get the actual numbers which are available in the air. If we do that, we can come to an estimate of the flux of droplets through a unique area and we can then use that figure to go on and interpret what is likely to land on any collecting surface we are interested in, such as tetse flys resting on branches or twigs.

Martin Houle:

You bring up a good point. That point that you bring up on calibration of droplet size is a good point. The rotorod must be calibrated to at least a range of droplet sizes. The problem with wind speed is that if you are in a canopy, and I assume this is where you were sampling, many times especially in the tropics the wind movement within the canopy or under the canopy itself is very still and that does cause, especially with a sampling device such as a rotorod, a resampling of the same area which as you point out you must correct for. However, if the rotorod sampler is used out in say a normal forest where you do get movement in amongst the trees, many times the principal advantage is that the rotorod sampler does mask out variability in the wind speeds, thus this thing that people have been spinning their wheels on trying to develop an isokinetic sampler in which it matches the wind speed exactly, that's always oriented into the wind, that's one of the principal advantages of the rotorod is that it does have a tendency, at least over a certain range of winds, to mask out variations in wind; but still winds, no, you have a problem, you have to correct like you pointed out. A good point.

John Spillman:

We've been doing some calibration of collection efficiencies of simple cylinders at Cranfield and we have found that the classical impaction parameter, the stop distance divided by the diameter or width of the catching cylinder, isn't a satisfactory basis. That diameter has a bigger effect I believe because of Reynolds number effects and that we find that we have to use two parameters to judge efficiency — catch efficiency — first of all the diameter and secondly the product of the sedimentation speed and the local wind speed. So if we are using cylindrical samplers in the field you really need to know quite accurately the size of sample you are collecting and also the local wind speed at the time it was sampled. Now the effective diameter is quite significant because we found that even with big droplets in high wind conditions, a sampler of 2 1/2 to 3 centimeters in diameter, your beer can, if you like, will never get a catch efficiency much more than 70%. Where as if you go down to things on the order of 1/2 a centimeter or less, then the catch efficiencies can go up 80-90%. The maximum you can get is something like 93% whatever you do.

SESSION V

MODELLING OF SPRAY CLOUD BEHAVIOUR

INTRODUCTION TO PROGRAM WIND

John W. Barry

USDA Forest Service

The USDA Forest Service (FS); the U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range; and the U.S. Army Dugway Proving Ground joined in the conduct of a major atmospheric study referred to as Program WIND. The Program was conducted in northern California during 1985–87. The field studies were conducted in a mountain-valley setting between Chico, CA and Red Bluff, CA, bounded on the west by Interstate 5, on the east by State Route 32, and on the north by State Route 36. The Program was managed by a USDA Forest Service Program Manager and a U.S. Army Deputy Program Manager. The Program Manager received policy and Program approvals from a policy committee that consisted of managers from both agencies.

The purpose of the study was to characterize atmospheric conditions by obtaining meteorological data during each of the four seasons and during different times of the day. Field data are being used to develop, evaluate, and enhance computer based mathematical models. The models being evaluated have suffered for need of a data base sophisticated enough to quantify the physical processes at play in the atmosphere. Theory can now be tested with and compared to reliable meteorological data obtained by the Program. These include models that predict (1) wind flow over a mountain-valley complex; (2) influence of forest and crop canopies on wind flow; (3) dispersion of smoke, air pollution, dust, pesticides, and other agricultural materials; and (4) effects of aircraft wake on dispersion of aerial sprays and dry materials.

Weather data were collected at 50 locations throughout the study area. There were 35 stations each consisting of a 10-meter mast which measured wind speed, wind direction, temperature, solar radiation and UV. Located at the other stations were towers which reached above the forest canopy, radiosondes, acoustical sounders, tethersondes, and sonic anemometers. Data acquisition is designed for efficient analyses and data access.

The FS is especially interested in models that predict spray drift, penetration, and deposition of sprays into and on forest/range canopies. Data collected during Program WIND will be used by the FS to develop and to make FS spray models simpler and easier to use in the field. In turn FS operations will be more efficient and effective.

The final phase was completed in October 1987. The success of Program WIND is attributed to the outstanding cooperation from all participants and cooperators; and especially that of the communities as represented by landowners and local governmental jurisdictions.

COMPARISONS OF AGDISP CODE PREDICTIONS WITH PROGRAM WIND DEPOSITION RESULTS

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ABSTRACT — Over the past two years, Program WIND (Winds in Nonuniform Domains) has had as a specific objective the collection of deposition and drift data of liquid sprays in flat and moderately complex forest and rangelands. This program, sponsored jointly by the USDA Forest Service and the DoD Atmospheric Science Laboratory, has assembled considerable aircraft flowfield and ground deposition data. Earlier ground deposition data collection programs provide additional field data to form a significant database with which to validate the Forest Service codes currently under development. In this paper the computer code AGDISP (AGricultural DISPersal) is summarized, and its predictions are compared favorably against a cross-section of the assembled data.

RÉSUMÉ — Au cours des deux dernières années, le programme WIND (Winds in Nonuniform Domains) a eu comme objectif spécifique la saisie de données sur le dépôt et la dérive de liquides pulvérisés sur des régions forestières planes et moyennement complexes et sur des régions montagneuses. Ce programme, parrainé conjointement par l'USDA Forest Service et le Laboratoire des sciences atmosphériques de la Défense nationale, a rassemblé une quantité considérable de données sur le champ d'écoulement des aéronefs et le dépôt au sol. Des programmes antérieurs de saisie de données sur le dépôt seul complètent les données sur les champs en une vaste base de données qui permet de valider les programmes du Forest Service qui sont en cours d'élaboration. Dans la présente communication, le programme informatique AGDISP (AGricultural DISPersal) est résumé, et ses prévisions sont comparées avantageusement à une coupe transversale des données rassemblées.

1. INTRODUCTION

The United States Department of Agriculture Forest Service has been engaged in the development and subsequent validation of computer codes designed to predict the deposition and drift of material released from aircraft. Development has centered on two computer codes, AGDISP and FSCBG (Forest Service Cramer-Barry-Grimm). AGDISP models the spray problem by a Lagrangian approach, and is discussed in this paper. The FSCBG code uses Gaussian plume modeling, and is reviewed in Dumbauld, et al. (1980).

Several specific deposition studies (Boyle, et al., 1957, Rafferty, et al., 1981, and Barry, et al., 1982) have been conducted by the USDA Forest Service and the US Army. These tests were used primarily to validate the FSCBG code. Recently, the USDA Forest Service has participated in Program WIND, with the objective of validating the AGDISP code and refining FSCBG predictions. The ground deposition data generated by these tests (Keetch, 1985 and 1986), combined with aircraft flowfield measurements by anemometer towers (Williamson, et al., 1985, and Teske, et al., 1986), provide a database with which to validate AGDISP. The purpose of this paper is to summarize the AGDISP computer code, and provide limited comparisons with these data.

Section 2 of this paper provides an historical review of the modeling present in the AGDISP code. Section 3 summarizes the current status of the code, and notes the references used to develop the models present in the code. Section 4 provides data comparison, and Section 5 offers conclusions and anticipated future developments.

2. HISTORY

The first analytical treatment of deposition and drift from agricultural aircraft is attributed to Reed (1954). In his pioneering report, Reed developed the Lagrangian equations of motion needed for the time dependent solution of the mean position and velocity of material released from nozzle locations along the trailing edge of a fixed-wing aircraft. His study acknowledged the importance of the aircraft wake in influencing material trajectories and ground deposition by representing the aircraft wake flowfield as a line vortex pair. Improvements to this technique, prior to the development of the AGDISP code in 1979, included the effects of propeller wash, crosswind and evaporation (Trayford and Welch, 1977), and bound circulation on the wing and limited three-dimensional effects in the vortex wake (Bragg, 1981 and 1986). In all of these models, the dispersion of the aerially released material resulting from atmospheric and aircraft wake turbulence was neglected.

Material released behind a fixed-wing aircraft, or beneath a helicopter rotor blade, enters a highly turbulent wake. To solve for the subsequent motion of the released material, and its eventual deposition, one must first either measure the aircraft wake flowfield into which the material is released, or analytically model the aircraft wake with best approximation.

By 1977, several of the authors of this paper had had extensive experience in modeling the turbulent wakes behind aircraft (Bilanin, et al., 1977 and 1978, and Hecht, et al., 1979), and similar flowfields that require an accurate description of turbulent transport (Lewellen, et al., 1974, 1976, 1978, 1979 and 1980, Lewellen and Teske, 1973, 1976 and 1977, and Teske and Lewellen, 1976, 1977, 1978 and 1979). These referenced technologies resulted in the development of the "VORTEX WAKE" computer code for NASA Langley (Teske, 1976). This code is available through COSMIC and uses second-order closure turbulent modeling (Donaldson, 1973, and Lewellen, 1977) to predict the decay of aircraft wakes. The VORTEX WAKE code and subsequent revisions are currently a research tool which has in the past been utilized to investigate the mechanism by which vortices interact with the atmosphere and the ground, and thereby decay.

The AGDISP code was developed with three objectives in mind:

1) the code had to accurately represent the aircraft wake, including turbulence effects on the material trajectory;

2) the code had to be able to make predictions rapidly; and

3) the code had to be easy to operate.

The first version of AGDISP was written with the idea of coupling VORTEX WAKE predicted flowfields to the Lagrangian trajectory solution. This feature remains, in fact, a little-used option in the current Mod 4 version of the code. The coupling, were it successful, would permit the computation of fixed-wing aircraft wake flowfields, and then, the prediction of released material trajectories and subsequent ground deposition.

It became obvious that the VORTEX WAKE code provided a wake flow description in far greater detail than was necessary at significant computer expense. Thus, attention turned to modeling the flowfield components and combining these models together to represent the wake behind an aircraft. This approach, suggested by Reed, became more attractive after second-order closure turbulent modeling was used to develop the material correlation equations (Bilanin and Teske, 1984). Relying on previous experience, we were able to model the growth due to turbulence of the standard deviation of the released material about its mean position, and develop Lagrangian closure equations for the correlations between the particle position and velocity fluctuations and the local fluid velocity fluctuations. In this way, the mean and standard deviation equations are solved at each nozzle location, for each assumed material diameter size. When the material approaches the ground, the calculation of deposition becomes straightforward since the known material magnitudes and standard deviation are known.

The initial success of the code, particularly in comparing with the NASA Langley experimental results conducted at Wallops Island, Virginia (Morris, et al., 1984), led the USDA Forest Service to support continued development. Additional flowfield models, code refinements and plotting and data presentation enhancements have been added in the last few years (Teske, 1984, 1985 and 1986), making AGDISP a powerful predictive tool for deposition and drift analysis.

3. CURRENT

The present status of the AGDISP code is summarized in Table 1.

Simple models that represent the particular fluid mechanics but are computationally efficient have been the goal in code development from its beginning. Thus:

1) The mean equations of motion developed by Reed (1954) have been implemented with an empirical drag coefficient law valid across a wide Reynolds number range (Langmuir and Blodgett, 1946), and have been extended to include the effects of turbulence on the standard deviation of the material trajectory (Bilanin and Teske, 1984).

2) Simple point vortices have been extended with the Betz roll-up methodology (Betz, 1933, and Bilanin and Donaldson, 1975).

3) Simple helicopter downwash models developed from actuator disk theory, transition to rolled-up vortices in time scales determined by complex helicopter wake models (Bliss, et al., 1984).

4) Jet engine and propeller modeling borrow from the similarity solution of Schlicting (1968) but include adaptation for turbulence effects from the data of Wygnanski and Fiedler (1969).

5) Aircraft wide-body effects are modeled from slender body theory (Ashley and Landahl, 1965) but include the effects of turbulent diffusion from the data of Chevray (1968).

6) Atmospheric crosswind profiles are selected from the logarithmic representation (Lumley and Panofsky, 1964) but with turbulent effects from second-order closure (Lewellen, 1977) and canopy profile adjustment from Wilson and Shaw (1977).

7) The option of specifying a flowfield experimental result for flowfield code prediction such as VORTEX WAKE is still retained.

The AGDISP code, from its first development as a research tool, has evolved through recent refinements to an easily used engineering tool. As an example, consider the flowfield of an aircraft wake as it approaches the ground. Figure 1, taken from Bilanin, et al. (1978), shows the vortices interacting with the ground and generating countersign vorticity which results in vortex bounce or rebound. It was first thought that this viscous interaction with the ground would significantly influence the ground deposition and would have to be included in the AGDISP code. In Figure 2 is shown the computed trajectories of the vortices. Those trajectories marked laminar or turbulent are computed including the viscous interaction with the ground. Those marked inviscid do not include the ground boundary layer interaction, and the vortices do not rebound from the ground. Curiously, for times $t^* = t\Gamma/2\pi s^2 = 4.0$, the trajectories are nearly identical. Here Γ is the circulation of the vortex and $2s$ is the initial separation between vortices. At this point, the countersign vorticity, generated in the boundary layer in response to the approaching vortex pair, forces the vortices to bounce away from the surface. Picot, et al. (1986) and Atias and Weihs (1984 and 1985) argue for including the vortex bounce effect, but fail to realize that material sizes above a volume median diameter of 150 microns will have deposited on the surface before the bounce occurs. For volume median diameters below 150 microns, a vortex bounce may in fact create more downwind drift, since material trapped around the vortex will tend to lift. However, our solutions show that ground deposition generally occurs during the descent of the vortex pair, no matter what the material size. This is fortunate and permits the use of fully rolled-up inviscid vortices as the flowfield model in the AGDISP code. This approximation eliminates the use of a VORTEX WAKE or similar viscous code, therefore resulting in considerable savings in computer time.

To be a good representation of the actual turbulent effects, inviscid point vortices should undergo vortex core diffusion and circulation strength decay as they descend to the surface. Circulation decay is modeled in AGDISP, developed from atmospheric decay analysis (Donaldson and Bilanin, 1975) and canopy interaction effects (Williamson, et al., 1985). Vortex core diffusion effects are currently being parameterized by comparison with Program WIND data.

The other modeling area is that of droplet evaporation of released material. In this area there are many models, but we prefer the simple model developed by Trayford and Welch (1977) based on ideas from Fuchs (1959). Comparing the predictions of this model with tunnel data by Dennison and Wedding (1984) gives the agreement for the solid curve shown in Figure 3. When a two-equation model (involving mass and energy) is developed from first principles (Kreith, 1966) and implemented with a Clausius-Clapeyron relationship, the prediction shown by the dashed curve in Figure 3 results. Clearly, either model is an adequate representation for evaporation effects.

The past shortcoming of the AGDISP code is its lack of a canopy deposition model. Such a model is currently under development.

4. DATA COMPARISON

Several of the models in AGDISP have been developed by parameterizing laboratory data. Thus, for example, the drag coefficient formula is taken as a curve fit from an extensive laboratory test. Some results, however, can be compared against specific laboratory data, such as the evaporation model discussed earlier. For the most part, however, we must rely on field tests to provide ground deposition data with which to compare predictions of the code.

Field tests, by their very nature, do not lend themselves to precise data collection. All of the parameters that could affect the material motion — aircraft weight, flight speed, altitude, material size and atmospheric wind conditions — usually carry some imprecision. Validation with AGDISP then involves comparing the ground deposition pattern data with AGDISP predictions. A satisfactory quantitative measure of error has yet to be suggested, and the current assessment of acceptability of the accuracy of the model is qualitative.

A large number of field tests are available to validate the predictions of the AGDISP code. We will look at only a sample of these comparisons. The field conditions for the tests to be discussed are summarized in Table 2. Complete comparisons for all tests encompassing Figure 4 may be found in Morris, et al. (1984), while complete comparisons for all tests at Chico, Dugway, Red Bluff and Withlacoochee may be found in Teske (1987).

Figure 4 compares the ground deposition for flight 53, run 1.2, during the NASA Langley Wallops Island tests (Morris, et al., 1984). In this study, 83 flight tests were undertaken using an Ayres Thrush, with and without winglets. The aircraft was flown at three to four meters above the surface, in a straight path over three card rows set 15 meters apart. Small polystyrene spheres of two sizes were released from two nozzles, one on each wing, through six ports in each nozzle. All of the data were collected and compared against AGDISP predictions. Crosswind tends to move the results off center, while the single propeller generally (and predictably) alters the standard deviation of the ground deposition pattern. In almost all cases the nozzle ports became clogged with spheres, so that an accurate experimental release flow rate was difficult to determine. To overcome this difficulty, the total experimental ground deposition from each nozzle was used to normalize the predicted ground deposition from the corresponding nozzle.

A typical Chico result is shown in Figure 5 for run B-2 with a Hiller 12E helicopter. The ground deposition data were recorded through the tree line of almond trees in an orchard, and at several other locations beneath and away from canopy cover. While the AGDISP code presently cannot account for mass deposited on the canopy vegetation, it is anticipated that AGDISP should bound the ground deposition. The six distinct spikes in the prediction are the locations of the aircraft flight paths. In this case, the AGDISP result was superimposed six times to produce the predicted curve in Figure 5. Better agreement with data could be made by a crosswind shift of the predictions to the left.

Figure 6 gives the AGDISP agreement with run 1-7 for a DC-7B at Dugway Proving Grounds, Utah. In this test, the aircraft was flown over three card rows spaced 183 meters apart. The aircraft dispersal system was modeled by positioning two nozzles at the three-quarters semispan location on either side of the fuselage. While the peak of the deposition is nearly predicted, the crosswind drift is clearly larger than what was measured. In addition, the ground deposition integral shows that only 25 percent of the material was deposited in the experiment (with the rest drifting downwind off the card grid), while the AGDISP code predicts that 50 percent deposited.

A typical Red Bluff comparison is shown in Figure 7 for run A-3 with the C-130. This site was heavily treed. The aircraft flew along card rows spaced 50 meters or more apart laterally. The distinctive feature of these predictions is the spiked deposition patterns corresponding to the aircraft passes over the data from the left and right wing nozzles. The C-130 results show the same spiked pattern as the ground deposition data, and also predicts the observed maximum deposition value.

Figures 8 and 9 give typical results for the Stearman biplane and Hughes 500C helicopter, respectively, at the Withlacoochee tree orchard, Florida. The ground deposition data shown on these figures are averaged over multiple card rows laid perpendicular to the aircraft flight path. Even with a canopy present, the AGDISP results are in qualitative agreement with the data. Each spike in the predicted ground deposition pattern is the result of a separate aircraft flight, combined together to give the overall deposition results.

It is clear from the above comparisons that an accurate set of data, including wind conditions, nozzle placements and aircraft flight conditions, is essential for code comparison. The wind speed and direction translate directly into crosswind velocity component and ambient atmospheric turbulence level. The aircraft spray lines must be determined accurately as well, so as to be combined properly to recover the superimposed ground deposition pattern. Approximations and assumptions were made in the above data comparisons to fill in data gaps, yet the predictions are in reasonable agreement with the data.

The other significant set of data not yet reduced and compared with AGDISP predictions are the tower anemometer data collected during Program WIND. Table 3 summarizes these data. It is our intent in 1988 to use this data to infer the position and strength of the aircraft vortices in the open field and entering the canopy, then use these results to parameterize vortex circulation strength decay and vortex core diffusion. The data are reduced by a least squares minimization technique that considers the local in-plane wind velocities to be represented by a vortex pair and its ground image. The test instrument configuration is depicted in Figure 10 where towers are shown supporting propellor anemometers. The vortex flowfield results in an instantaneous velocity field shown in Figure 11. The vortex positions are computed from a data reduction algorithm. Since vortex descent and lateral translation are a direct influence on drift and deposition, the correct modeling of this flowfield cannot be overemphasized. In Figure 12 is shown the measured and predicted vortex strength lateral position, y, and height, z, as a function of time for the wake of a helicopter or fixed-wing aircraft. In the coming year, reduction and analysis of this data set is anticipated.

5. CONCLUSIONS

AGDISP has been shown to be a code that can predict deposition and drift in agricultural and forest spray applications. The present effort is in implementing a canopy deposition model, and comparing AGDISP vortex flowfield predictions with Program WIND tower anemometer data. By next fall, the validated AGDISP code will be made available to the Forest Service through technology transfer workshops conducted by Oregon State University, Corvallis, Oregon. Then, given meteorological measurements, a reference of aircraft characteristics (such as Hardy, 1987) and details about the material to be sprayed, AGDISP will yield accurate test predictions over the breadth of spray missions envisioned by the USDA Forest Service.

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TABLE 1: AGDISP Features

Under development since 1979.

Predicts the motion of aerially released material, including the mean position of the material and the position variance about the mean as a result of turbulent fluctuations.

Lagrangian solution approach

Includes simplified models for:

- Vortices (including Betz roll-up)
- Helicopter downwash and forward flight
- Jet engines
- Propellers
- Fuselage wide-body effects
- Atmospheric crosswind
- Vortex and downwash canopy penetration
- Terrain
- Vortex circulation strength decay
- Vortex core diffusion (1988)

Alternately, the code may be linked to a VORTEX WAKE result

Material Evaporation

Ground deposition

- Gaussian deposition on surface impact
- Continuous deposition as the material nears the surface (1988)
- Canopy deposition (1988)
- Deposition on vertical surfaces (1988)

Operational on:

- NASA Langley Cyber 175 (available through COSMIC)
- USDA Forest Service Fort Collins Univac 1108
- Dugway Proving Grounds DEC 11/785 (also DEC MicroVAX II)
- IBM PC/XT/AT or compatibles
- USDA Forest Service Data Generals (nationwide 1988)

Implemented as a subset of FSCBG for multiple particle sizes and aircraft passes, transitioning to Gaussian plume modeling.

Extensive ground deposition data comparisons for both fixed-wing aircraft and helicopters:

NASA Langley Wallops	Ayres Thrush
Program WIND Chico	Schweizer AgCat
	Hiller 12E helicopter
Dugway Army	DC-7B
Program WIND Red Bluff	C-130
	Bell Ranger 205 helicopter
Forest Service Withlacoochee	Stearman
	Hughes 500C helicopter
Gypsy Moth Mission	Cessna AgTruck (1988)

Vortex flowfield comparisons: Program WIND (1988)

TABLE 2: Field Deposition Conditions for AGDISP Comparisons

Location	Wallops	Chico	Dugway	Red Bluff	Withlacoochee
Aircraft	Ayres Thrush	AgCat Hiller 12E	DC-7B	C-130 Bell Ranger 206	Stearman Hughes 500C
Runs	83	10	5	12	8
Passes per Run	1	6	1	1 to 10	7 to 10
Altitude (m)	3 to 4	12.2	27 to 52	15.2 to 76.2	14.6 or 18.8
Nozzles	2	6 28	150	50 or 64 34	27 48
Spray Rate (gal/min)	—	20.5 5.4	25 or 26	116 or 149 12.2	27.3 7.6
VMD (microns)	300	189 251	50 to 68	394 264	350 350
Condition	open field	almond orchard	open field	forested	seed tree orchard

TABLE 3: Tower Anemometer Conditions for AGDISP Comparisons

Location	Foresthill	Chico	Red Bluff
Aircraft	AgHusky Bell Ranger 206	AgCat Hiller 12E	C-130 Bell Ranger 206
Runs	58 71	109	49
Condition	open field forested	almond orchard	open drainage

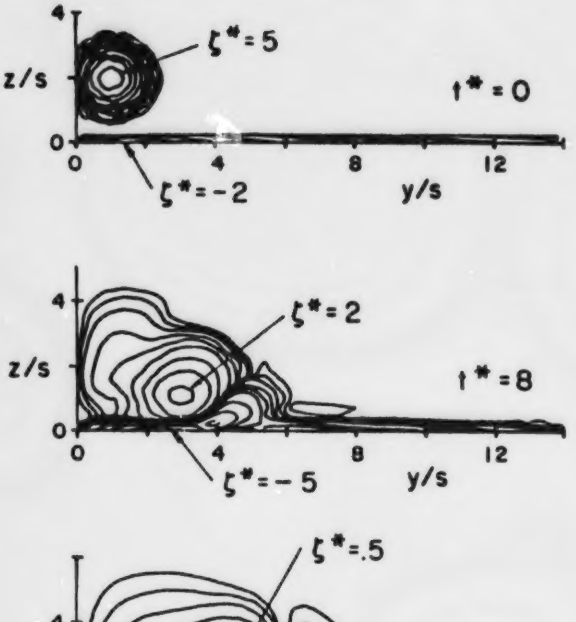


FIGURE 1: ISOPLETHS OF VORTICITY FOR A VORTEX PAIR DESCENDING TOWARD A GROUND PLANE. POSITIVE CONTOURS AROUND THE VORTEX FOLLOW THE VALUES: $\xi^* = \xi 2\pi s^2/\Gamma$ EQUAL TO 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, 0.01 AND 0.005. NEGATIVE CONTOURS GENERATED NEAR THE SURFACE FOLLOW −5, −2, −1, −0.5, −0.2, −0.1, −0.05, −0.02, −0.01 AND −0.005.

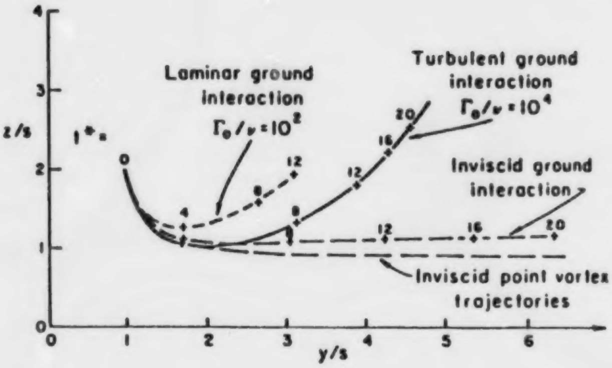


FIGURE 2: TRAJECTORIES OF THE MAXIMUM VALUE OF PASSIVE TRACER CARRIED BY A VORTEX PAIR DESCENDING ONTO A GROUND PLANE (BILANIN, ET AL., 1978).

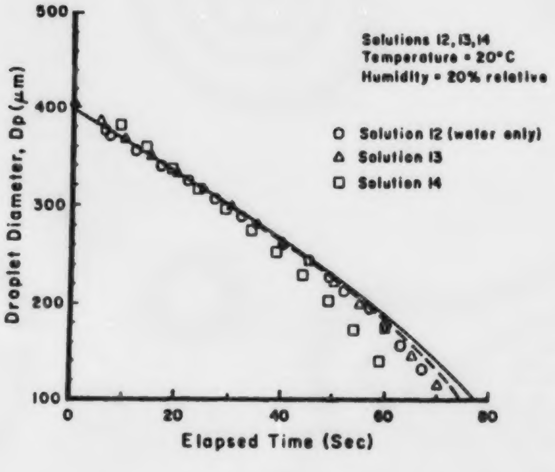


FIGURE 3: COMPARISON OF MODELS WITH THE EVAPORATION DATA OF DENNISON AND WEDDING (1984). SOLID CURVE IS THE WET BULB TEMPERATURE DEPRESSION MODEL OF TRAYFORD AND WELCH (1977). DASHED CURVE IS THE TWO-EQUATION MODEL OF KREITH (1966).

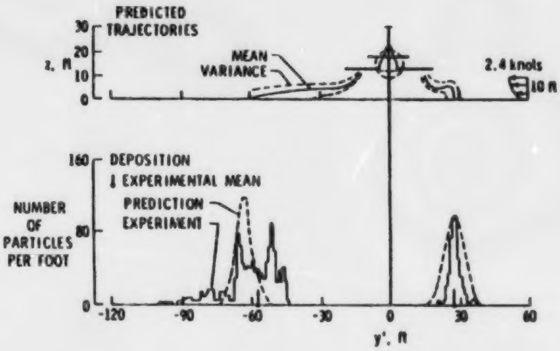


FIGURE 4: COMPARISON OF MEASURED AND PREDICTED GROUND DEPOSITION PATTERN FOR 300 MICRON SPHERES RELEASED AT 70 PERCENT SEMISPAN DURING FLIGHT AT 90 KNOTS IN A 2.4 KNOT CROSSWIND (MORRIS, ET AL., 1984).

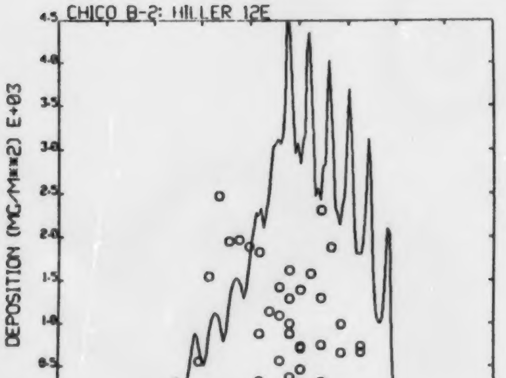


FIGURE 5: PREDICTED (SOLID CURVE) AND MEASURED (OPEN CIRCLES) GROUND DEPOSITION PATTERN FOR RUN B-2 AT CHICO.

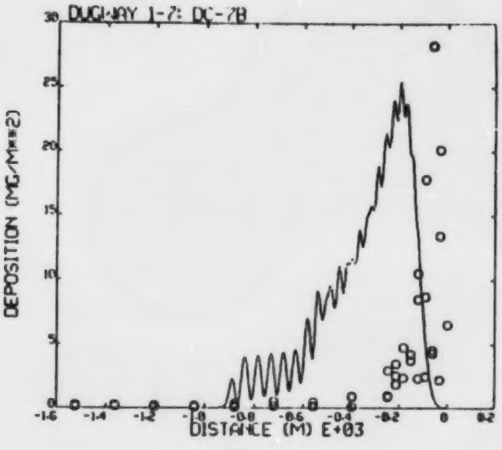


FIGURE 6: PREDICTED (SOLID CURVE) AND MEASURED (OPEN CIRCLES) GROUND DEPOSITION PATTERN FOR RUN 1-7 AT DUGWAY.

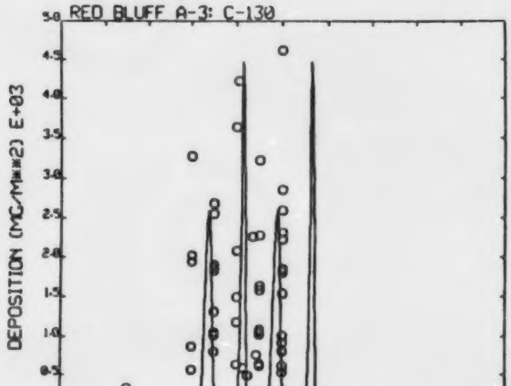


FIGURE 7: PREDICTED (SOLID CURVE) AND MEASURED (OPEN CIRCLES) GROUND DEPOSITION PATTERN FOR RUN A-3 AT RED BLUFF.

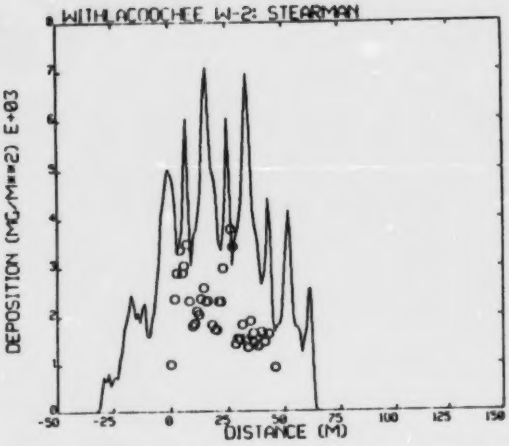


FIGURE 8: PREDICTED (SOLID CURVE) AND AVERAGED MEASURED (OPEN CIRCLES) GROUND DEPOSITION PATTERN FOR RUN W-2 AT WITHLACOOCHEE.

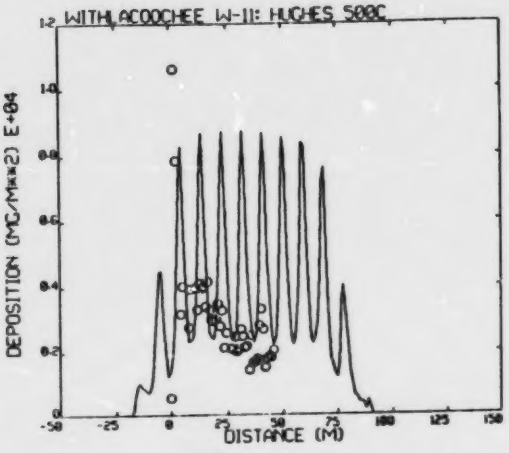


FIGURE 9: PREDICTED (SOLID CURVE) AND AVERAGED MEASURED (OPEN CIRCLES) GROUND DEPOSITION PATTERN FOR RUN W-11 AT WITHLACOOCHEE.

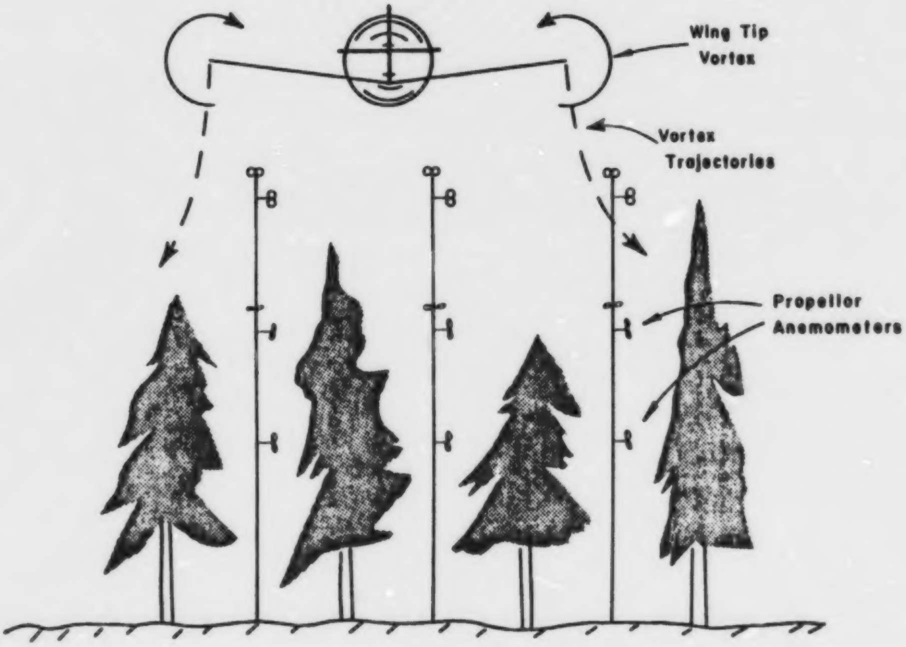

Wing Tip
Vortex
Vortex
Trajectories
Propellor
Anemometers
Vortex Canopy Interaction Tests

FIGURE 10: VORTEX POSITION IS DETERMINED BY COMPARISON OF THE OUTPUT OF THE PROPELLOR ANEMOMETERS WITH AN ANALYTIC MODEL OF THE VORTEX PAIR IN GROUND EFFECT.

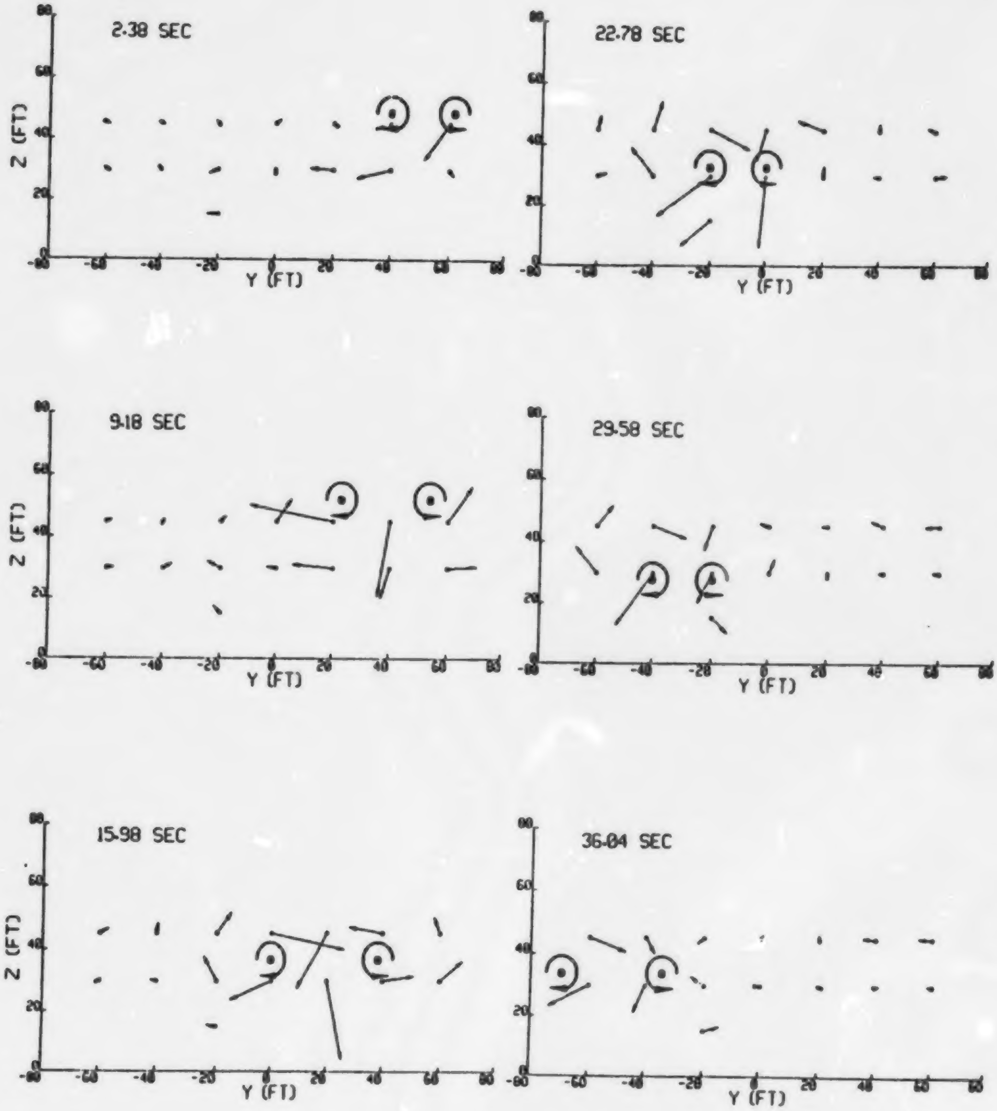
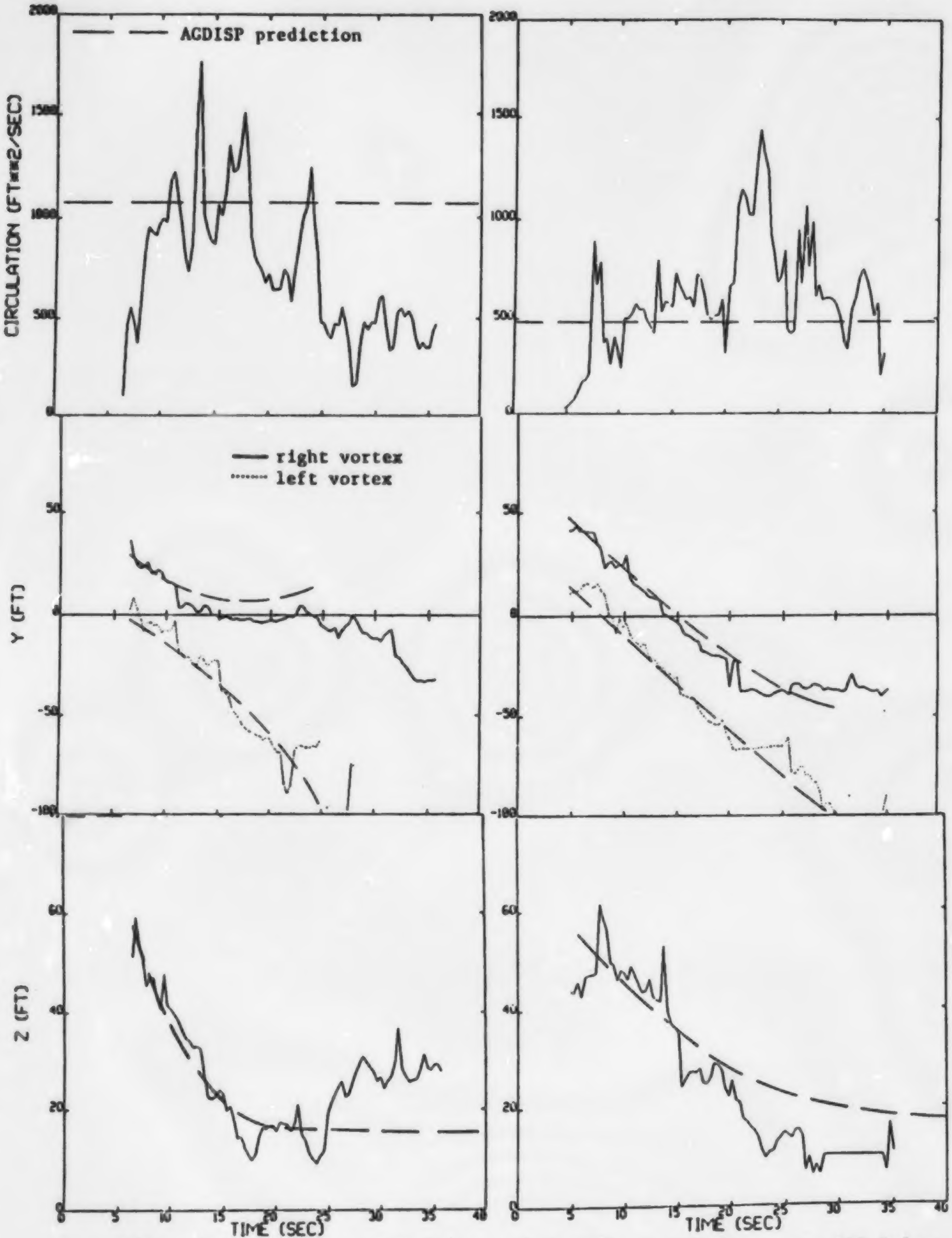


FIGURE 11: THE PREDICTED SPATIAL POSITION OF THE VORTEX PAIR AT SEVERAL TIMES IN RUN F058, FORESTHILL. THE ARROWS REPRESENT THE DIRECTION AND RELATIVE STRENGTH OF THE ANEMOMETER TOWER DATA AT THE TIMES NOTED.



Test F009 h = 60 ft v = 117 ft/sec

Test F058 h = 60 ft v = 117 ft/sec

FIGURE 12: TIME HISTORIES OF CIRCULATION AND SPATIAL POSITIONS OF THE VORTEX PAIR FROM THE OPEN FIELD AT FORESTHILL, COMPARED WITH AGDISP PREDICTIONS. TEST F009 ON THE LEFT IS WITH A BELL RANGER 206, WHILE TEST F058 ON THE RIGHT IS WITH AN AGHUSKY.

APPLICATION OF THE FSCBG VERSION 2 AERIAL SPRAY MODEL IN FORESTRY

by
Harry V. Geary[1], Clinton R. Bowman[2],
James E. Rafferty[3], and Richard K. Dumbauld[4]

ABSTRACT – The original FSCBG aerial spray model began as the combination of the Monte Carlo canopy penetration model of Grim and Barry (1975) and the Gaussian dispersion model of Cramer (1972) and was released in 1980. It computed evaporation and used a very simple model to account for wake effects. The model has been modified considerably since then and now, as FSCBG Version 2, it incorporates the more complete wake effects of the AGDISP model (Teske, 1986), substitutes an analytic replacement for the Monte Carlo canopy penetration model, and provides a new user-friendly menu-driven data input section. The current version is written in Fortran 77 (ANSI X3.9) and may with minor modifications run on computers as small as the IBM PC/XT. As part of the model evaluation process, the model output has been compared with selected data obtained during Phase III of Program WIND which was conducted in Northern California during 1986. This paper discusses the available data used to define model inputs, the field observations used for the comparison data set and the model/data comparison itself. The number of trials available for the comparison was insufficient to define the model strengths and limitations in any detail.

RÉSUMÉ – Le modèle de pulvérisation par voie aérienne FSCBG original consistait en une combinaison du modèle de pénétration du couvert forestier de Monte Carlo de Grim et Barry (1975) et du modèle de dispersion gaussienne de Cramer (1972), et a été mis au point en 1980. Il calculait l'évaporation et s'appuyait sur un modèle très simple pour tenir compte des effets de sillage. Le modèle a été modifié considérablement depuis ce temps, et maintenant, dans la version 2 FSCBG, il tient compte des effets de sillage plus complets du modèle AGDISP (Teske, 1986), remplace par une démarche analytique le modèle de pénétration du couvert de Monte Carlo, et produit une nouvelle section pour l'entrée des données qui est basée sur un menu et qui est facile d'utilisation. La version actuelle est rédigée en Fortran 77 (ANSI X3.9) et peut, à quelques modifications près, être exécutée sur des ordinateurs aussi petits que le PC/XT d'IBM. Dans le cadre du processus d'évaluation du modèle, les résultats du modèle ont été comparés à un choix de données obtenu pendant la phase III du programme WIND qui a été réalisé en Californie du Nord en 1986. La présente communication porte sur les données disponibles utilisées pour définir les données d'entrée du modèle, sur les observations prises sur le terrain en vue de constituer l'ensemble de données de comparaison et sur la comparaison modèle/données elle-même. Le nombre d'essais disponibles pour la comparaison était insuffisant pour définir dans le détail les forces et les faiblesses du modèle.

INTRODUCTION

Purpose of the Paper

The purpose of this paper is to present the results of modeling the Program WIND, Phase III trials which were conducted in Northern California during April and May of 1986. The Phase III trials were part of a cooperative study between the USDA Forest Service and the US Army to establish a data base of meteorological and dispersion measurements applicable to regions of varying vegetative cover in complex terrain.

General Description of the FSCBG Version 2 Computer Program

The FSCBG Version 2 aerial spray model is a general purpose program suitable for modeling the fate of droplets and vapors associated with spray operations from the point of emission to final deposition or evaporation. The model incorporates the AGDISP aircraft wake algorithm to model the effects of aircraft wakes on drop trajectories. It can model the effects of both fixed and rotary wing aircraft. The FSCBG Version 2 computer program includes an algorithm to compute the evaporation of the drops and accounts for the conversion of liquid to gas phase in computing dosage and concentration. The penetration of drops through a plant canopy of up to three stories can be calculated. A Gaussian line source dispersion model computes the dispersion of drops and vapors to determine at user-specified points the dosage, concentration, and/or deposition of the material emitted into the atmosphere. Deposition due to the direct impaction of drops under the influence of aircraft wakes is also accounted for. Written in Fortran 77 (ANSI X3.9) and running on computers as small as the IBM PC/XT, FSCBG Version 2 provides comprehensive user assistance in defining the parameters required to execute the program.

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Development

The FSCBG Version 2 aerial spray model began as the combination of the Monte Carlo canopy penetration model of Grim and Barry (1975) and the Gaussian dispersion model of Cramer (1972). By the time the original version of FSCBG was released (Dumbauld, *et al.*, 1980), it included mathematical models for aircraft wake effects, line source dispersion, drop evaporation, and canopy penetration. It subsequently was used to model spray operations from Florida to Maine to Montana. It rapidly became apparent that although the model demonstrated considerable skill in computing deposition and dosage/concentration, there were certain parts of the model that needed improvement: the Monte Carlo canopy penetration algorithm accounted for a major portion of the execution time; the simplified aircraft wake model only roughly accounted for wake descent and the effect of vortices on source size; and, what was possibly the most important shortcoming, the considerable work required by the user to set up the inputs for even the simplest run.

DISCUSSION

Framework of FSCBG Version 2

The FSCBG Version 2 aerial spray program is divided into four main parts: input, model calculation, output, and graphics. The input is driven from two main menus which determine which models the user has chosen to run and which data needs to be entered or reviewed. In the input part, the user has the option to redirect the printed and graphical output, to use a previously entered input parameter list in defining the default values, or to use some previously calculated evaporation, canopy penetration, aircraft wake, or dispersion calculations. Naturally, options exist to save some or all of the above. Aircraft specifications can be defined for certain aircraft by just choosing the desired model from a list. Much of the data manipulation previously required to define the meteorological variables has been eliminated, allowing the user to enter measured data.

The more complete wake model from AGDISP has been incorporated to compute the initial positions for the dispersion calculations of drops emitted from nozzles. This wake model includes the effects of wing tip vortices; propellers and jet exit nozzles; wide body aircraft; Betz, triangular, and rectangular roll-up; and rotary wing aircraft in both hover and forward advance. It also accounts for the cross-track wind velocity and the effects of atmospheric turbulence on wake decay, drop velocities, and drop positions.

The canopy penetration modeling has been improved by the development of the analytic penetration model so that the canopy penetration calculations now take only a small fraction of the total execution time. The printed output can be redirected to a file or logical unit and printed or examined at the user's convenience. The graphical output may be displayed on a number of devices from Tektronix and VAX terminals to Calcomp plotters.

Almost any computer supporting a Fortran 77 (ANSI X3.9) program of 750 k bytes is capable of hosting FSCBG Version 2 and, although the graphical output is available for a wide variety of devices, compatibility is not required to obtain the printed output.

METHOD

Program WIND, Phase III Trials

The Phase III trials of Program WIND were conducted in the Northern California foothills of the Sierra Nevada approximately 100 km east of Red Bluff, CA. The site was on the western edge of a predominately second-growth ponderosa pine forest and included two other vegetation types: a Christmas tree plantation and a brush-covered gully (Klein and Boom, 1987). In the forested area, slightly fewer than half of the 320 trees per hectare were ponderosa pine, half were incense cedar, about one-tenth were oak species, and there was an occasional Douglas fir. The upper story of the canopy was composed exclusively of the ponderosa pine with a mean height of 24 meters, the oak species defined a second story at eight meters, and the incense cedar defined the lowest story with an average height of five meters. The Christmas tree plantation, measuring approximately 900 by 1200 meters, was composed of short trees (heights less than 50 cm) and the height of the brush in the gully, which transects the plantation, averaged about one meter.

In addition to the variations in ground cover, the region is dominated by a general slope of the terrain downward toward the west. The terrain is also crossed with a network of gullies which would be expected to affect the wind flow in the region. It was anticipated that the average nocturnal wind direction would be from the east and would persist for several hours after sunrise. Therefore, the spray lines were set up along north-south tracks a few hundred meters east of the forest-plantation boundary and the sampling grid was oriented so that its long dimension was roughly east-west with the densest part of the grid in the vicinity of and just to the west of the spray lines. However, as with all carefully made plans, synoptic factors dominated the expected local conditions for some of the trials.

The sampling grid consisted of 82 Kromekote deposition sampling cards measuring 11 by 17 cm inserted into plastic holders and placed on the ground. The dense part of the grid was composed of north-south rows of cards with inter-card spacings from 25 to 100 meters. The spacing between rows was generally 50 meters in the dense portion of the grid. The grid extended from about 500 meters east (planned upwind direction) of the spray lines to more than 2 kilometers to the west (downwind). A series of six sampling points extended in a southwest direction roughly down the gully. Mylar sheets were set out at the same locations to measure mass deposition. There were also other Kromekote cards set out on vertical lines but these have not been included in the present analysis. An apparent error in the spread factor coefficients precluded the use of the Kromekote data and all deposition data were obtained from the Mylar sheets. Therefore, no evaluation of drop sizes as a function of downwind distance could be made.

Data from three 32-meter-tall meteorological data towers, four low-level (2-meter) wind stations, and a meteorological observer were used to define the meteorological conditions for each trial modeled. The towers carried instruments to measure temperature, relative humidity, and three components of wind speed at eight levels (approximately 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.1, and 1.2 times the canopy height of 24 meters). Other parameters were measured on the towers but that data have not been processed and were not available for this study. The low-level wind stations reported air and soil temperatures, wind direction, and wind speed. The data from the low-level wind stations was used only to supplement the tower data. One of the towers was located in the young Christmas tree plantation approximately 350 meters west of the forest edge. Data from this tower was used to define the "in the open" meteorological variables. A second tower was placed within the forest, about 150 meters east of the plantation boundary. This tower and another located 300 meters deeper into the forest were used to define the meteorological variables under the canopy and in the transition region which can extend as high as twice the height of the canopy. The observer supplied sky cover and other information which was used to confirm the automatically measured tower data. The rawinsonde and Doppler acoustic sounder data have not been processed and were unavailable for this study. As will be seen below, the absence of data between 30 meters above the ground and the flight level severely limited the confidence in the model/data comparisons.

Ten trials were conducted during Phase III, six using a C-130H and four using a Bell 206. Two trials were rejected as being unsuitable for modeling because of large directional wind shifts which occurred during the time the sprayed material would be passing through the sampling grid. Complications with some of the other eight trials included wet cards, small but still significant wind shifts, and cross-grid wind directions.

Two aircraft were used in the spray operations, the C-130H and the Bell 206. The C-130H is a large, wide-bodied, four-engine cargo transport with a flight weight of 51 000 kilograms, a wing span of 40 meters, and a spray delivery speed of 100 meters per second. The spray booms were carried 0.6 meters below the wings, outboard of the engines, and had 50 Tee Jet 8020 nozzles open during the spray delivery. Practical considerations required that the nozzles be grouped for the modeling; six groups were used in the present modeling. The C-130H was used in the trials beginning with A- in Table 1. In each trial the C-130H made two spray passes over the dense part of the grid. The spray lines were between 1.5 and 2 kilometers long, centered on the grid centerline in a north to south direction. Spray times varied between 10 and 15 seconds. Application rates varied from 70 to 100 grams per meter and the flight altitude was varied between 50 and 75 meters above the ground (25 to 50 meters above the top of the canopy).

The Bell 206 helicopter is a small, widely used utility helicopter outfitted with two spray booms. The Bell 206 has a gross weight of 1450 kilograms, a rotor diameter of 10 meters, and a spray delivery speed of 25 meters per second. The spray booms are carried below the helicopter body and extend five meters to each side. Each boom has 29 nozzles; but only 17 were used in the B- trials listed in Table 1. Modeling was done using 4 nozzles. The helicopter made from six to ten spraying passes, each lasting between 30 and 40 seconds for total line lengths of approximately 1000 meters. The application rate varied from 33 to 50 grams per meter and the flight altitude was constant at 45 meters above the ground.

Modeling of the Phase III Trials

Only three of the four models in FSCBG Version 2 were used to model the Phase III trials; the addition of one-third part glycerine to the water, red dye, manganese sulphate mixture reduces evaporation to negligible levels. The drop size distributions were measured by Yates *et al.* (1984) in a wind tunnel. The Tee Jet 8020 nozzle used on the C-130H produced a spray with a volume median diameter of 185 micrometers at an airspeed of 75 meters per second (the highest speed measured in the wind tunnel). Dissemination at the delivery airspeed of 100 meters per second used in the Program WIND trials would be expected to reduce the median. However, the absence of the Kromekote data prevented any estimate of the magnitude of the reduction. The D4-45 nozzle used on the Bell 206 produced a spray with a volume median diameter of 292 micrometers. The aircraft characteristics of the C-130H and the Bell 206 are contained in the FSCBG Version 2 default list and only the weight and the nozzle locations were changed.

The FSCBG Version 2 program requires definition of the following canopy characteristics: the story height, the stand density, the envelop of a representative member of each story, the probability of horizontal penetration through the largest diameter of the tree, and the characteristic size of individual vegetative elements. Data contained in Klein and Boom (1987) was used to define the story height and the stand density and to estimate the envelop dimensions, the probability of horizontal penetration, and the characteristic size. The characteristic vegetative element size was 13, 8, and 8 cm for the ponderosa, oak, and incense cedar canopies, respectively. The probability of horizontal penetration for the three canopies was set equal to 0.62, 0.38, and 0.33, respectively.

The meteorological data was processed to reduce the data rate from the one second averages archived on tapes supplied by the US Army Atmospheric Sciences Laboratory to a ten minute average which is more representative of atmospheric conditions required by Gaussian models. Since the dispersion time extended for more than ten minutes for all trials and the dissemination time lasted for more than ten minutes for some of the trials, several ten-minute averages were averaged to obtain the most representative values of the meteorological variables. For most of the trials, the four successive ten-minute averages beginning with the ten minutes immediately prior to the start of the spraying were averaged. Data limitations and non-stationary conditions reduced the number of ten-minute samples used in the average to as few as one for some of the trials. Below canopy wind speeds fluctuated about the minimum measurable speed in six of the trials making the definition of wind speeds within the canopy difficult. The meteorological conditions used in the modeling are listed in Tables 2 through 6.

Most of the trials are characterized by wind speed profiles that are well described by the power law with correlation coefficients greater than 0.89. All of the trials were conducted shortly after sunrise and the temperature profile measured on the tower in the open showed a definite inversion for nearly every trial.

RESULTS

Although all eight of the trials identified above as being satisfactory trials were modeled, the sampling data from the three trials with cross-grid wind directions (A-3, B-1, and B-2) are insufficient in spatial extent to permit a meaningful comparison with the model calculations. Although the wind direction is nearly at right angles to both the spray lines and the sampling rows in the remaining five trials, there was enough variability in the deposition levels along each row, that row averages are being used for comparison with the modeling results. These average values are shown by the open circles in Figures 1 through 5. Interpretation of these figures which compare the model computed deposition with the measured deposition will be aided by the following explanation. In all cases the wind is blowing from left to right in the direction of increasing distance. The region to the left of the 500 meter distance lies within the ponderosa pine forest; the Christmas tree plantation lies to the right (downwind). The row-averaged deposition has been subjectively analyzed and that analysis is shown as a solid line in the figures. In some cases the large variation of the data is indicated by a pair of dotted lines roughly enclosing the envelope of the observed deposition values. All trials were modeled both with the forest canopy (valid to the left of the 500 meter distance) and without a canopy (valid at some unknown distance to the right of the 500 meter distance). The region of the aircraft flight tracks is indicated by a small aircraft symbol with the location of each track shown by a small vertical line extending upward from the abscissa.

The following describes the significant issues and conclusions for each trial compared. Two points should be recognized in the interpretation of these model/data comparisons: first, the trial data being used are incomplete and were furnished in an unedited form specifically for this study and, secondly, this is the first major modeling study done with the FSCBG Version 2 computer program. Although there are no known program bugs which would produce erroneous results, the amount of experience with this new version is limited.

Trial A-2

Trial A-2 took place under high overcast conditions with the solar elevation angle less than 12 degrees. Beginning at ten minutes before the spray dissemination time the wind speed decreased slightly over a twenty minute period and then quickly recovered and remained constant for the next twenty minutes. The average values of the turbulent intensities near the ground increased as the wind speed decreased, but both the wind speeds and turbulent intensities at heights greater than ten meters above the ground were unchanged. The temperature profile which exhibited a strong inversion of two degrees Celsius warming between the 2.4 and the 30 meter levels during the ten minutes before the spray runs, decreased to only 0.6 degrees. The wind direction veered by 20 degrees, increasing from 99 degrees at the 2.4 meter level to 119 degrees at 30 meters above the ground. The lack of meteorological data at heights between 30 meters and the flight altitude of 76 meters prevents an adequate definition of the turbulence parameters and the wind speed and direction in the region where the aircraft wake would be expected to have the greatest effect.

In Figure 1 it can be seen that the model predicts the location of the region of maximum ground-level deposition to occur at the forest boundary at approximately the same place shown by the measurements. The model predicts a peak deposition of slightly more than twice the level that was measured and the modeled deposition levels fall off faster than the measured levels.

Trial A-4

Trial A-4 took place under nearly clear skies with temperature initially increasing with height. However, by the end of the second 10-minute period after the spray dissemination time, the temperature profile was approaching neutral. As the temperature profile changed, the wind speed decreased and the measured turbulent intensities increased. By the second 10-minute period after the spray dissemination time, the wind direction had become highly variable.

Figure 2 shows the comparison of the model calculated deposition with the measured deposition for Trial A-4. The comparison is quantitatively very similar to that in the previous figure for Trial A-2.

Trial A-6

Trial A-6 took place under nearly clear skies with the temperature profile showing a ground based inversion through the lowest 30 meters. The meteorological conditions are quite stationary; only the turbulent intensities show much change during the four 10-minute periods used to define the meteorological parameters for the modeling.

Although the model predicts the location of the maximum deposition to be 150 meters inside the forest (about halfway between the spray lines and the forest edge), the greatest measured deposition occurred almost under the downwind spray line. The data shows more scatter within the forest than any other trial modeled and about the same amount of scatter as Trial A-2 in the region downwind of the forest edge. The model does not seem to do as well in modeling this "nearly ideal" trial as it does the others; the maximum modeled deposition is more than four times the smoothed peak of the measured deposition (although the modeled is less than three times the measured peak row-averaged deposition).

Trial B-3

Trial B-3 took place under high, overcast skies and with a ground-based inversion indicated in the temperature profile. Meteorological conditions were nearly constant during the four 10-minute periods used to define the parameters for the modeling.

The model results are quite close to the measured; the maximum calculated deposition is less than 1.5 times that measured and the position of the peak is predicted to occur only 60 meters downwind of the row with the highest average deposition. The modeled deposition pattern does drop off faster in the downwind direction than was observed and by approximately one kilometer downwind is only one-third of the observed deposition.

Trial B-4

Trial B-4 was conducted under nearly cloudless skies with a moderately strong inversion extending from the 2.4 meter level up through the 30 meter level. The first two 10-minute periods were characterized by wind speed decreasing with height, the third 10-minute period had a nearly parabolic wind speed profile with its maximum speed at a height of 14 meters. Only during the fourth 10-minute period (when only the smallest drops could possibly still be aloft) did the wind speed profile approach the familiar power law. During the first two periods, the wind direction veered by nearly 65 degrees between the lowest and highest levels on the tower. By the fourth period the difference in direction between the top and bottom had decreased to less than ten degrees. As can be seen in Figure 5, trial B-4 has the most dramatic tail of any of the trials. The deposition levels remain nearly constant downwind of the forest boundary.

The modeled deposition pattern has its peak at the same location as the measured deposition pattern but is slightly less than twice as large and the deposition levels fall off faster than those measured.

Model Performance

It is difficult to assess model performance on the basis of only five model/data comparisons using what must be termed preliminary and incomplete data to define the meteorological parameters. On the basis of the results shown in Figures 1 through 5, the FSCBG Version 2 forest spray model accurately models the position of the maximum ground-level deposition, but may overpredict the deposition level in the vicinity of the maximum and the computed deposition levels decrease faster with downwind distance than observed. A general review of the measured meteorological parameters reveals that the turbulent intensities are somewhat lower than expected. However the lack of measurements between the top of the tower and the aircraft flight altitude coupled with the absence of any clear-cut profile in the turbulent intensities precludes making rational changes to the values used in the modeling.

SUMMARY

It would be premature to try to gauge the strengths and weaknesses of any model on the basis of such a limited evaluation. Certainly, the basic parts of the FSCBG Version 2 aerial spray model have demonstrated skill in computing deposition. The original FSCBG model was used in many studies by both the USDA Forest Service and the US Army to predict both deposition and dosage/concentration. The AGDISP wake model has also been under development for an extensive length of time and has shown considerable skill in describing the air motions associated with aircraft wakes and their effects on drop trajectories. The model/data comparison completed in this preliminary application supports the conclusion that the FSCBG Version 2 aerial spray model will provide realistic and useful predictions of deposition. This study is only the first of several which must be done to fully assess the strengths and weaknesses of the new code.

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TABLE 1:
Summary of Trial Meteorological Data

Trial	Date	Time	Wind Direction	Wind Speed	Comments
			***** C-130H *****		
A-1	23 April	0653	100–200	1.0	Large wind shift during trial
A-2	24 April	0621	108	2.9	Moderate wind shift 0640
A-3	25 April	0743	191	2.6	Cross-grid wind direction, data collection terminated at 0745
A-4	26 April	0612	098	3.5	Good trial
A-5	27 April	0710	120–170	1.0	Large wind shift
A-6	28 April	0653	109	2.8	Good Trial
			***** BELL 206 *****		
B-1	01 May	0701	166	3.6	Cross-grid wind direction
B-2	02 May	0652	160	10.0	Cross-grid wind direction
B-3	06 May	0651	110	4.0	Wet cards
B-4	07 May	0657	115	2.0	Wet cards, moderate directional and speed changes

TABLE 2:
Trial A-2 OPEN Tower (40-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	6.49	1.13	99.5	9.230	2.003
2	4.9	6.26	1.59	102.2	5.900	1.770
3	9.7	6.38	2.24	103.3	1.796	1.952
4	14.3	6.69	2.72	101.9	1.579	2.198
5	19.2	7.10	2.82	105.8	4.072	2.567
6	24.1	7.47	2.63	110.7	6.937	2.656
7	27.1	7.51	2.46	114.1	7.373	3.114
8	30.2	7.70	2.28	119.9	7.119	3.339
AVERAGE					5.501	2.450

Trial A-2 CANOPY Tower (40-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	10.72	0.21	157.0	63.84	0.95
2	4.9	10.83	0.23	154.3	60.98	6.34
3	9.7	10.90	0.12	193.7	73.32	44.50
4	14.3	10.98	0.26	149.7	67.16	43.79
5	19.2	11.10	0.61	167.9	46.38	29.76
6	24.1	11.30	1.10	169.7	34.47	20.24
AVERAGE		10.97	0.42	165.4		

TABLE 3:
Trial A-4 OPEN Tower (40-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	5.38	0.78	120.2	32.19	3.56
2	4.9	5.28	1.02	74.9	36.65	3.46
3	9.7	5.34	1.27	63.7	32.29	5.37
4	14.3	5.21	1.41	69.8	28.48	6.45
5	19.2	5.20	1.54	76.8	25.52	6.20
6	24.1	5.21	1.71	78.6	14.76	4.40
7	27.1	5.10	1.70	79.5	11.00	4.00
8	30.2	5.33	2.10	83.5	9.54	3.19
AVERAGE					23.80	4.58

Trial A-4 CANOPY Tower (10-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	0.54	0.10	89.6	29.59	0.68
2	4.9	0.73	0.10	61.8	31.11	0.94
3	9.7	1.02	0.02	89.8	22.48	17.94
4	14.3	1.56	0.14	74.9	52.32	24.21
5	19.2	2.69	0.37	86.4	19.77	14.68
6	24.1	3.93	0.70	91.7	19.66	10.62
AVERAGE		1.75	0.24	82.4		

TABLE 4:
Trial A-6 OPEN (40-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	7.24	1.01	96.5	6.070	1.182
2	4.9	7.39	1.08	102.5	6.091	0.893
3	9.7	7.63	1.56	105.7	3.272	1.394
4	14.3	7.48	1.90	105.3	3.925	1.318
5	19.2	7.69	2.17	107.9	4.037	2.107
6	24.1	7.92	2.26	110.9	5.385	1.766
7	27.1	8.00	2.21	114.0	6.273	1.865
8	30.2	8.28	2.27	118.8	6.188	1.604
AVERAGE					5.155	1.516

Trial A-6 CANOPY Tower (10-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	3.55	0.16	90.0	0.00	0.72
2	4.9	3.71	0.11	85.4	21.15	0.00
3	9.7	3.91	0.00	90.0	0.00	0.00
4	14.3	3.90	0.21	89.4	1.64	0.00
5	19.2	4.25	0.33	90.0	0.00	0.52
6	24.1	5.86	0.40	89.4	1.71	0.71
AVERAGE		4.20	0.20	89.0		

TABLE 5:
Trial B-3 OPEN Tower (40-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	0.35	2.13	102.9	7.420	1.518
2	4.9	0.36	2.32	106[illegible]	6.086	1.405
3	9.7	0.55	2.82	108.0	5.005	2.164
4	14.3	0.51	3.14	105.8	5.260	2.367
5	19.2	0.60	3.44	106.9	5.242	1.925
6	24.1	0.80	3.65	108.8	6.420	2.129
7	27.1	0.88	3.68	110.6	6.024	3.084
8	30.2	1.08	4.10	113.6	4.330	2.733
AVERAGE					5.723	2.166

Trial B-3 CANOPY Tower (40-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	−0.24	0.00	64.8	39.21	36.76
2	4.9	−0.14	0.00	52.2	43.25	83.56
3	9.7	−0.17	0.00	45.6	44.06	243.51
4	14.3	0.03	0.00	51.4	42.24	66.61
5	19.2	0.18	0.01	43.1	42.44	36.76
6	24.1	0.62	0.33	151.8	36.14	30.18
AVERAGE		0.25	0.36	79.1		

TABLE 6:
Trial B-4 OPEN Tower (40-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	3.27	1.32	97.6	8.027	1.175
2	4.9	3.36	1.41	103.9	7.406	1.246
3	9.7	3.99	1.81	108.7	7.105	1.494
4	14.3	4.17	1.87	111.5	8.820	1.901
5	19.2	4.59	1.82	117.2	9.814	1.293
6	24.1	4.76	1.67	124.7	11.749	2.368
7	27.1	4.91	1.55	130.3	14.592	3.262
8	30.2	5.26	1.48	138.9	16.958	3.373
AVERAGE					10.559	2.014

Trial B-4 CANOPY Tower (10-min average)

Level	Z	Temp	Wind Speed	Wind Dir	SIGA	SIGE
1	2.4	−0.38	0.00	180.0	0.00	0.00
2	4.9	−0.57	0.00	270.0	0.00	0.00
3	9.7	−0.42	0.00	0.0	0.00	0.00
4	14.3	−0.50	0.00	254.6	34.30	114.59
5	19.2	0.11	0.00	211.0	60.93	0.00
6	24.1	1.64	0.33	90.6	2.65	1.21
AVERAGE		−0.02	0.06	****		

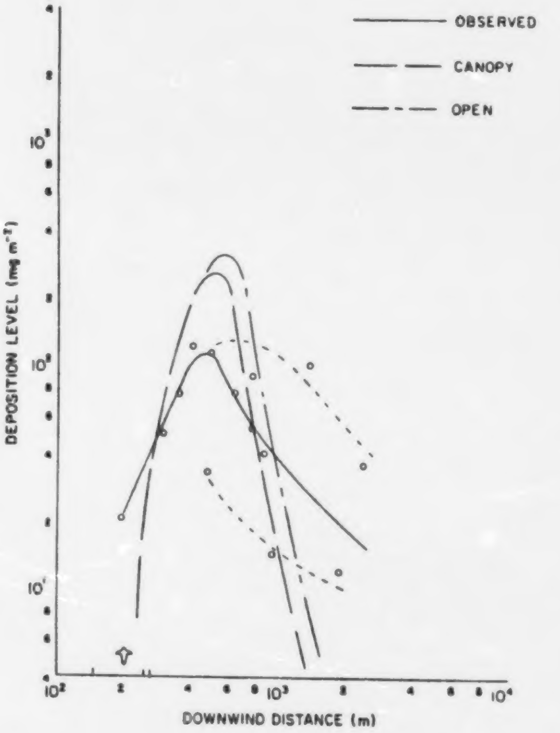

FIGURE 1: WIND TRIAL A-2 DATA AND FSCBG V2 OUTPUT

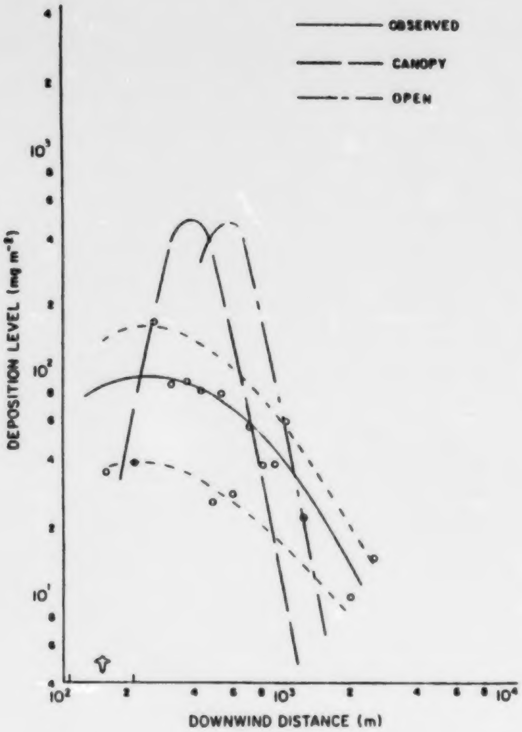

FIGURE 2: WIND TRIAL A-4 DATA AND FSCBG V2 OUPUT

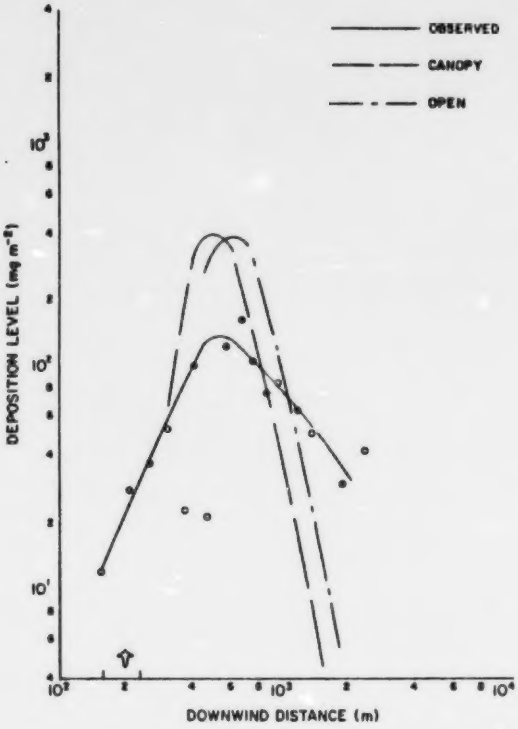

FIGURE 3: WIND TRIAL A-6 DATA AND FSCBG V2 OUTPUT

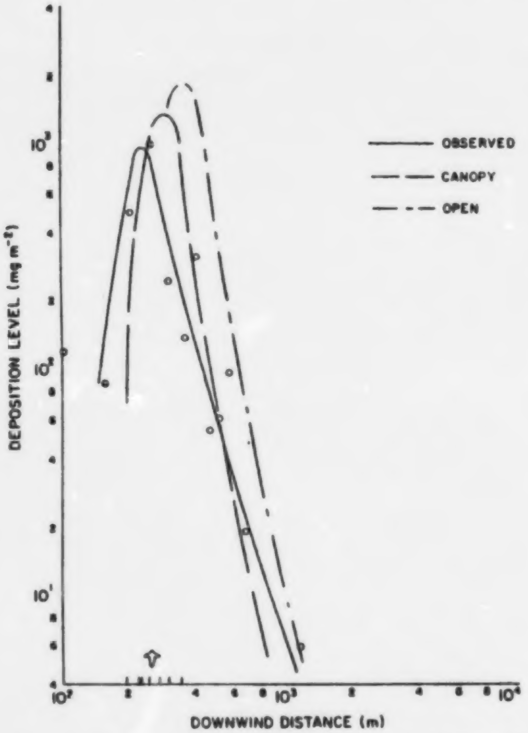

FIGURE 4: WIND TRIAL B-3 DATA AND FSCBG V2 OUPTUT

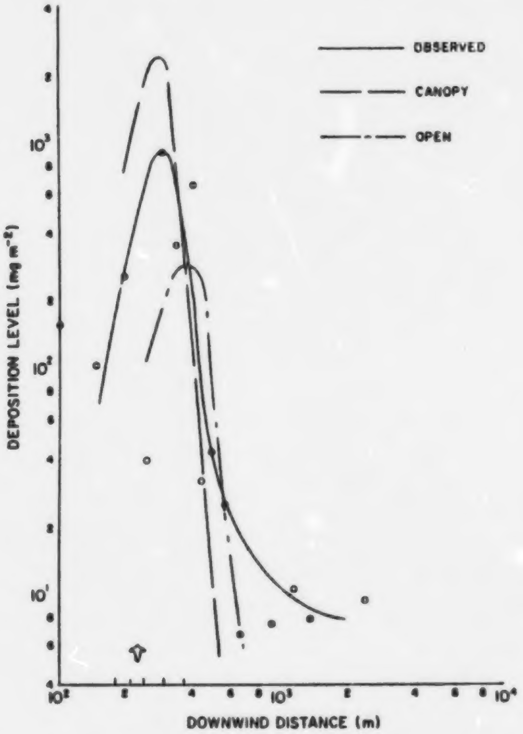

FIGURE 5: WIND TRIAL B-4 DATA AND FSCBG V2 OUTPUT

INTRODUCTION TO THE DUNPHY EXPERIMENT

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The annual ultra-low-volume (ULV) insecticide spray program in New Brunswick has protected the forests against damage from the spruce budworm since its inception in 1952. At the same time, it has generated expressions of public concern for the environmental impact of the aerial spray emissions on non-target receptors. In 1981, the NRC proposed to the spray agency, Forest Protection Ltd. of New Brunswick, a series of controlled field studies in the Dunphy, New Brunswick forests to determine those meteorological conditions most conducive to suppressing off-target wind-borne droplet drift and enhancing target deposition. Data are presented showing that thermally neutral to unstable turbulent boundary-layer flow yields the lowest drift cloud mass at one kilometer from the flight line while thermally stable (non-turbulent) boundary layer flow yields the largest. This result dispels the widely-held belief that ULV aerial spraying must be conducted in the thermally stable conditions of early morning/late evening, rather than in turbulent conditions of midday, in order to avoid long range environmental contamination.

THE PKBW MODEL FOR PREDICTION OF AERIAL SPRAYING DEPOSITION AND DRIFT

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ABSTRACT — Second order closure turbulence modelling and Lagrangian trajector modelling are used to compute aircraft wake vortex flow patterns and aerial spray droplet dispersion in the atmosphere in the PKBW model. Droplet trajectories are computed from vortex velocities until the vortex decays into background turbulence, then a Monte Carlo type Markov chain process is used to give particle movement based on Lagrangian turbulence scales for the atmosphere. Spray atomizer droplet emission spectrum is a model input and droplet evaporation is taken into account. Droplet deposition on foliage is computed using a foliage interception and droplet impaction efficiency model which is species (tree) specific. Computations of droplet collection on foliage, on ground, and in suspension are carried out as a function of time for a range ot spray parameters.

Comparison of model results versus field trial data for Grumman TBM Avenger and Cessna Agtruck aircraft under a range of conditions (stable, neutral, and unstable atmospheric conditions) shows that on average, for canopy deposit in the 0 to 400 m downwind zone, the model shows 35% higher canopy deposit and 19% higher off-target drift values than experimental values, which are themselves subject to some errror.

Parametric studies show a strong dependency of foliage deposit and off-target drift on aircraft spray height in agreement with field trial observation. The PKBW model is an excellent tool for optimization of aerial spray methodology.

RÉSUMÉ — Une modélisation de la turbulence de fermeture de deuxième ordre et une modélisation lagrangienne des trajectoires sont utilisées pour calculer l'écoulement turbulent dans le sillage d'un aéronef et la dispersion des gouttelettes pulvérisées par voie aérienne dans l'atmosphère, dans le modèle PKBW. Les trajectoires des gouttelettes sont calculés à partir des vitesses du tourbillon jusqu'à ce que le tourbillon s'atténue en turbulence de fond, puis une chaîne de Markov de type Monte Carlo est utilisée pour donner aux particules un mouvement basé sur des échelles lagrangiennes de turbulence pour l'atmosphère. Le spectre d'émission de gouttelettes d'un pulvérisateur est une donnée d'entrée du modèle, et l'évaporation des gouttelettes est prise en compte. Le dépôt des gouttelettes sur le feuillage est calculé à l'aide d'un modèle de rendement interception par le feuillage/impact des gouttelettes qui est spécifique à l'essence (arbre). Des calculs du nombre de gouttelettes recueillies sur le feuillage, sur le sol et en suspension sont effectués en fonction du temps pour une gamme de paramètres de pulvérisation.

La comparaison des résultats du modèle et des données d'essai sur le terrain pour les appareils Grumman TBM et Cessna Agtruck et pour une gamme de conditions atmosphériques (stable, neutre et instable) révèlent qu'en moyenne, dans les premiers 400 m sous le vent, le modèle calcule un dépôt sur le couvert forestier de 35 % supérieur et des valeurs de dérive hors cible de 19 % supérieures aux valeurs expérimentales qui sont elles-mêmes sujettes à une certaine marge d'erreur.

Des études paramétriques indiquent que le dépôt sur le feuillage et la dérive hors cible dépendent fortement de la hauteur de pulvérisation de l'aéronef, conformément aux résultats des essais sur le terrain. Le modèle PKBW est un excellent outil d'optimisation des méthodes de pulvérisation par voie aérienne.

INTRODUCTION

Aerial spraying to control the spruce budworm (*Choristoneura fumiferana* (Clemens)) has been carried out for a number of years in New Brunswick to protect fir and spruce forests from excessive defoliation. Recent research has aimed at increasing the deposition of insecticide on the forest canopy and reducing off-target drift. An important element in this research is the computer simulation of the overall process of spray generation, dispersion, and deposition. The PKBW model (*P*icot, *K*ristmanson, *B*asak, *W*allace) described here calculates droplet concentrations in the atmosphere, and deposit on foliage and ground as functions of time after release from the aircraft. The model incorporates the effects of aircraft vortex, its interaction with a turbulent atmosphere, the atomizer droplet generation characteristics, droplet evaporation, droplet transport in the atmosphere, droplet impaction on foliage and deposition on ground, and droplet off-target drift.

The simulation model is composed of two main components. The first is a modification of the VORTEX WAKE code developed by the Aeronautical Research Associates of Princeton (A.R.A.P.) and is described below from a paper by Wallace and

Picot (1987). This is a second order closure turbulence model. The second part is a Lagrangian atmospheric dispersion model described by Picot et al. (1986). Droplet trajectories for 4000 droplets in each size class are calculated from the point of generation on the wing to the point of deposition or off-target drift. The calculation takes into account aircraft design and operating parameters, atomizer operation parameters, weather parameters, and forest stand characteristics such as foliage particle collection efficiency and vertical foliage density distribution by species.

The model is demonstrated herein by comparing its output against field trial data gathered in recent experiments carried out by the New Brunswick Spray Efficacy Research Group. The model is then used to indicate fruitful avenues of development for aerial spray technology in the context of aerial spraying in coniferous forests.

MODEL DESCRIPTION

1. VORTEX WAKE SEGMENT.

i) General.

A variety of inviscid methods (Brashears et al., 1975; Brandt and Iverson, 1977; Raj and Iverson, 1978; Rossow, 1978) have been proposed to explain vortex wake interaction with a ground plane and cross wind shear. Bilanin, Teske and Williamson (1977) and later, Bilanin, Teske and Hirsh (1978) advanced a model which accounted for the viscous and turbulent nature of diffusion associated with wake behaviour in a turbulent atmosphere. They used an invariant, second order closure model developed by Donaldson (1973) to solve the Reynolds stress equations for the two dimensional problem of vortex dispersion in the atmosphere. The study herein reports on the application of the above modelling technique under neutral, stable and unstable atmospheric conditions.

The equations governing the motion of a viscous, turbulent, incompressible fluid are derived by incorporating mean and fluctuating components for the independent variables u and P into the cartesian equations for continuity and momentum. For parallel shear flow in which $\bar{u} = u\ (z)$, $\bar{v} = \delta/\delta y = O$ $\bar{w} << \bar{u}$ and $\delta/\delta x << \delta/\delta z$, a set of equations for the mean variables $\bar{u}$, $\bar{w}$, $\bar{P}$, and the Reynolds stresses, $\overline{u'u'}$, $\overline{w'w'}$, $\overline{v'v'}$, and $\overline{u'w'}$, can be obtained. Expressing the mean velocities and the pressure in terms of the vorticity transport equation, we have:

$$\frac{Dn}{Dt} = \frac{g}{\varrho_o}\frac{\delta\varrho}{\delta y} - \frac{\delta^2\overline{u'w'}}{\delta z^2} - \frac{\delta^2(\overline{u'u'} - \overline{w'w'})}{\delta y \delta z} + \frac{\delta^2\overline{u'w'}}{\delta y^2} \qquad (1)$$

$$+ \frac{1}{Re}\left(\frac{\delta^2\eta}{\delta y^2} + \frac{\delta^2\eta}{\delta z^2}\right)$$

where
$$\frac{D(\ )}{Dt} = \frac{\delta(\ )}{\delta t} + \frac{\delta\bar{u}(\ )}{\delta y} + \frac{\delta\bar{w}(\ )}{\delta z} \qquad (2)$$

and where $\bar{u}$ and $\bar{w}$ are solved from the Poisson equation for the stream function ψ:

$$-\eta = \frac{\delta^2\psi}{\delta y^2} + \frac{\delta^2\psi}{\delta z^2} \qquad (3)$$

with $\bar{u} = -\frac{\delta\psi}{\delta z}$ and $\bar{w} = \frac{\delta\psi}{\delta y}$ (4)

For stable and unstable atmospheric conditions in which a gradient in the mean temperature is imposed, an additional equation for energy must be solved for:

$$\frac{D\bar{T}}{Dt} = \frac{\delta\overline{u'T'}}{\delta y} - \frac{\delta\overline{\bar{w}'T'}}{\delta z} + \frac{1}{Pr}\left(\frac{\delta^2\bar{T}}{\delta y^2} + \frac{\delta^2\bar{T}}{\delta z^2}\right) \qquad (5)$$

The generalized equation for the Reynolds stresses is:

$$\frac{D\,\overline{u_j'u_k'}}{Dt} = \underset{(a)}{-\overline{u_j'u_k'}\ \frac{\delta\bar{u}_i}{\delta x_j}}\ \underset{(b)}{-\overline{u_j'u_i'}\ \frac{\delta\bar{u}_k}{\delta x_j}} + \underset{(c)}{\frac{1}{T_o}(g_i\overline{u_j'T'} + g_j\overline{u_i'T'})}$$

$$\underset{(d)}{\frac{\delta(\overline{u_i'u_j'u_k'})}{\delta xj}} - \underset{(e)}{\frac{1}{\varrho_o}\left(\frac{\delta\overline{P'u_i'}}{\delta x_k} + \frac{\delta\overline{P'u_k'}}{\delta x_i}\right)} + \underset{(f)}{\frac{P'}{\varrho_o}\left(\frac{\delta u_i'}{\delta x_k} + \frac{\delta u_k'}{\delta x_i}\right)}$$

$$+ \underset{(g)}{\nu_o\frac{\delta^2\overline{u_j'u_k'}}{\delta x_j{}^2}} - \underset{(h)}{2\,\nu_o\frac{\delta\overline{u_i'u_k'}}{\delta x_j\delta x_j}} \qquad (6)$$

with the equation for the turbulent heat fluxes as:

$$\frac{D\overline{u_k'T'}}{DT} = \underset{(a)}{-\overline{u_i'u_k'}\frac{\delta\bar{T}}{\delta x_j}} - \underset{(b)}{\overline{u_j'T'}\frac{\delta\bar{u}_k}{\delta x_j}} + \underset{(c)}{\frac{1}{T_o}\ g_k\ \overline{T'^2}}$$

$$\underset{(d)}{-\frac{\delta}{\delta x_j}(\overline{u_j'u_k'T'})} - \underset{(e)}{\frac{1}{\varrho_o}\ \frac{\delta}{\delta x_k}(\overline{P'T'})} + \underset{(f)}{\overline{\frac{p'}{\varrho_o}\ \frac{\delta T'}{\delta x_k}}}$$

$$+ \underset{(g)}{\upsilon_o\frac{\delta^2\overline{u_k'T'}}{\delta x_j{}^2}} - \underset{(h)}{2\,\upsilon_o\frac{\delta\overline{u_k'\delta T'}}{\delta x_j\delta x_j}} \qquad (7)$$

and for $\overline{T'T'}$: (8)

$$\frac{D\overline{T'^2}}{Dt} = \underset{(a)}{-2\overline{u_j'T'}\ \frac{\delta\bar{T}}{\delta x_j}} - \underset{(d)}{\frac{\delta\overline{u_j'T'^2}}{\delta x_j}} + \underset{(g)}{\nu_o\frac{\delta^2\overline{T'^2}}{\delta x_j}} \underset{(h)}{-2\nu_o\,\frac{\overline{\delta T'}}{\delta x_j}\ \frac{\overline{\delta T'}}{\delta x_j}}$$

Closure is achieved in the above set of equations using an invariant technique developed by Donaldson (1973) in which the velocity diffusion terms (d), pressure diffusion terms (e), tendency towards isotropy terms (f) and molecular dissipation terms (h) are modelled. The invariant closure model however does require definition of a length scale, Λ. For the boundary layer problem being considered in which Z is the vertical distance from the ground, Λ is taken as:

$$\Lambda = 0.5\ Z \qquad (9)$$

The computer code, VORTEX WAKE, solves equations (1) and (5)-(8) using a finite difference Alternating Direction Implicit (ADI) technique (Peaceman and Rachford, 1955) for each one half time step. For each complete time step, the vorticity is used to solve the streamfunction ψ from the Poisson equation (3). A fast direct method (Swarztrauber and Sweet, 1975) is employed. The mean velocities, $\bar{u}$ and $\bar{w}$, are then computed and updated from (4).

ii) Initial Conditions.

The computations are initialized with two counter rotating, fully rolled up vortices centered at ± bπ/8 from the aircraft centerline, where b is the aircraft wingspan (Figure 1). Gaussians of vorticity, η and turbulence, q^2, define the vortices at the prescribed centers. If the vortex core is treated as a solid cylinder rotating about its axis, the maximum vorticity can be calculated from the circulation, Γ, for half the wingspan (Bilanin et al., 1977):

$$\eta = \Gamma / (r_c^2 \times \pi) \tag{10}$$

where r_c is the vortex core radius and

$$\Gamma = (4\ Wg) / (\pi \varrho U b) \tag{11}$$

for an elliptically loaded wing (Hallock & Eberle, 1977).

Wg and U are the aircraft weight and speed respectively, and ϱ is the air density. Values of r, W and U for the TBM and Ag-truck used in the NBSERG field trials are given in Table 1.

The value chosen for the turbulence level, q^2, was one which could be supported in an atmosphere of light to moderate turbulence (Tombach, 1973) where the dissipation rate $e^{1/3} = 2\ \mathrm{cm}^{2/3}/\mathrm{sec}$. If the dissipation is written as $e = 0.125\ q^3/\Lambda$ (Bilanin et al., 1977), than $q^2 = 0.27\ \mathrm{m}^2/\mathrm{sec}^2$, where $\Lambda = 0.5 \times Z_{HT}$, and where Z_{HT} is arbitrarily chosen for all runs as 40 m.

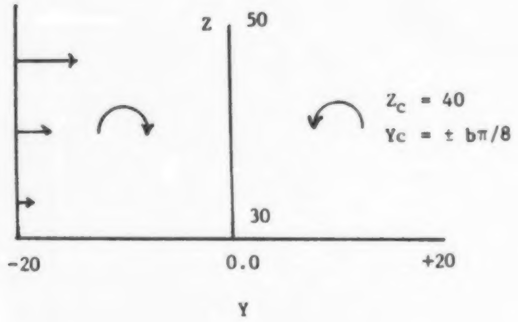

FIGURE 1: TYPICAL CONDITIONS FOR COMPUTATIONAL DOMAIN WITH CROSS WIND SHEAR.

TABLE 1: Aircraft Parameters

		TBM		AGT	
b	m (ft), wingspan	16.5	(54.1)	12.6	(41.3)
r_c	m (ft), vortex radius	0.3	(1.0)	0.3	(1.0)
W	kg (lbs)	8172	(18019)	1904	(4198)
u	m/sec (ft. sec), aircraft speed	77	(253)	49	(161)
Γ	m^2/sec (ft^2/sec), circulation	66	(710)	32	(344)
η	(sec^{-1}), maximum vorticity	233		111	

iii) Boundary Conditions.

A cross wind shear was imposed by specifying the normal gradient in the stream function along the boundaries. From (4), this represents the horizontal velocity component $\bar{u}$ on the top and bottom boundaries and the vertical velocity component $\bar{w}$ on the sides. The vertical velocities along the sides were set to zero, and the horizontal component $\bar{u}$ on the top and bottom boundaries were computed from equations 25, 26 and 27. The vorticity along the upper and lower boundaries were computed from:

$$\eta = \frac{\delta \bar{u}}{\delta z} = \left(\frac{u_j - u_{j-1}}{z_j - z_{j-1}}\right) \tag{12}$$

Along the sides the vorticity was defined by a zero derivative boundary condition. The upper and lower boundary values for the turbulent correlations were determined by an application of Donaldson's superequilibrium theory (Donaldson, 1973). Under superequilibrium conditions, the diffusion, dissipation, and rate terms in equations (6), (7) and (8) are negligible. The equations can then be solved for q^2, $\overline{u_i' u_j'}$, $\overline{u_i' T'}$, and $\overline{T'T'}$ if a velocity gradient and length scale are specified and if:

$$q^2 = \overline{u'u'} + \overline{w'w'} + \overline{v'v'} \tag{13}$$

To solve for the turbulent correlations, the velocity gradient and length scale were computed from a reference height of 30 metres (98 ft). The solution to this set of equations for the turbulent correlations was used as the upper and lower boundary values. Zero derivative boundary conditions were applied to the sides for these variables.

2. LAGRANGIAN ATMOSPHERIC DISPERSION SEGMENT

i) General.

This portion is a Monte Carlo Lagrangian type of model using a Markov chain process for vertical turbulent velocity fluctuations. This was used by Reid (1979) to simulate particle dispersion and deposition in a neutral atmosphere and was subsequently extended to other stability classes by Wilson (1980, 1982). This portion of the PKBW model "takes over" the trajectory calculation after vortex wake effects have decayed into atmospheric background levels. Droplet trajectory steps are calculated as follows:

$$\begin{aligned} \Delta x &= \bar{u}(z)\Delta t \\ \Delta z &= w(z)\Delta t \end{aligned} \tag{14}$$

Here Δx and Δz represent horizontal and vertical movements of the droplet based on mean horizontal wind components $\bar{u}(z)$, instantaneous vertical wind components $w(z)$, and Lagrangian time step Δt. This Δt is chosen as one-tenth of the Lagrangian time scale τ_L at the point in question. This time scale is defined using the Lagrangian autocorrelation function as follows:

$$\tau_L(z) = \int_0^\infty R_L(z,t)dt$$

and

$$R_L(z,t) = \frac{\overline{u'(t,z)\ u'\ (t+\Delta t,z)}}{\overline{u'^2}} \tag{15}$$

is the autocorrelation function calculated with the moving particle as reference. When Δt is sufficiently small, the autocorrelation function can be approximated by:

$$R_L = \exp(-\Delta t/\tau_L) \tag{16}$$

The instantaneous vertical velocity component w(z) is then constructed as follows:

$$w(z) = w_L(t) + w_B + w_g \tag{17}$$

Here w_g is the terminal settling velocity for the droplet in still air, a readily available quantity (Perry (1973)), w_B is the "bias velocity" required to preserve uniform density in a non-homogeneous turbulence atmosphere (see below) and $w_L(t)$ is constructed as a Markov chain process as follows:

$$w_L(t)=w_L(t-\Delta t)\exp(-\Delta t/\tau_L)+\{1-\exp(-2\Delta t/\tau_L)\}^{1/2}\sigma_w r(t) \tag{18}$$

Here σ_w is the turbulent velocity scale, in general dependent on z, and r(t) is a random number generated with mean zero and a standard deviation of unity. The bias velocity term is required since in a situation where σ_w is not constant, the calculation scheme would predict a net vertical flux when applied to the atmosphere itself. The bias velocity therefore provides a net correcting flux which forces compliance with the principle of a uniform atmospheric density in the case of a negligible vertical pressure gradient (Legg, B.J. and M.R. Raupach (1982)). A number of alternatives for expressing this have been tested, and the following gives adequate results with the constant β equal to 0.5 below z_T (tree height) for the neutral and unstable cases:

$$w_B = \beta\tau_L \frac{\partial(\sigma_w^2)}{\partial z} \tag{19}$$

Above z_T, $W_B = 0$.

This has been found to produce minimal segregation of droplets for a test where droplets are given zero settling velocity, and zero deposition efficiency, with reflection from the top of the mixing layer and from ground (i.e., the particles simulate the motion of gas molecules in the atmosphere under conditions of zero net flux).

The following correlations are used for τ_L, σ_w, and u(z):

τ_L: Neutral atmosphere: $$\tau_L(z) = \frac{0.5z}{\sigma_w} \tag{20}$$

Stable atmosphere: $$\tau_L(z) = \frac{0.5z}{\sigma_w}(1+5\frac{z}{L})^{-1} \tag{21}$$

Unstable atmosphere: $$\tau_L(z) = \frac{0.5z}{\sigma_w}(1-6\frac{z}{L})^{1/4} \tag{22}$$

σ_w: Neutral and stable: $$\sigma_w = 1.25\,u^* \tag{23}$$

Unstable: $$\sigma_w = 1.25\,u^*(1-4.1\frac{z}{L})^{1/3} \tag{24}$$

u(z): Neutral: $$\bar{u}(z) = \frac{u^*}{k}\ln[\frac{z-d}{z_0}] \tag{25}$$

Stable: $$\bar{u}(z): = \frac{u^*}{k}[\ln\frac{z}{z_0} + \frac{4.7}{L}(z-z_0)] \tag{26}$$

Unstable: $$\bar{u}(z) = \int_{z_0}^{z}\frac{u^*}{kz}(1-16\frac{z}{L})^{-1/4}\,dz \tag{27}$$

In these equations, the following definitions are necessary:

L = Monin-Obukhov length = $(-\varrho c_p T_o u^{*3})/(kgH)$
z_0 = roughness height (1.44 m (4.72 ft) for current tests)
d = displacement height (11.25 m (36.9 ft) herein)
k = velocity profile constant (0.4)
H = vertical heat flux in atmosphere
u^* = friction velocity
T_o = temperature of ground level

The vertical height dependency expressed in the above correlations is valid some distance above the mean tree height. Crabbe et al. (1983) gives the mean tree height as the value determined visually (15 m (49.2 ft)) by observers stationed on various meteorological towers and observation platforms in the test plot. This is higher than the value obtained (10.7 m (35.1 ft)) by averaging all tree heights in the sample plots but is in agreement with the usual value (~0.8) obtained by dividing displacement height by mean tree height, indicating a "masking" of the smallest trees in this particular stand. Following Belot et al. (1976) the following expression is used for horizontal wind components u(z) below mean tree height z_T (15 m, (49.2 ft)):

$$\bar{u}(z) = \bar{u}(z_T)\exp[-\alpha(1-\frac{z}{z_T})] \tag{28}$$

The constant α has values of 2.5 for neutral and 6 for both stable and unstable conditions. This relation is used down to 0.5 z_T from which level downwards velocity is assumed constant. Correlations are also needed for σ_w and τ_L in the foliage canopy region. Values of σ_w and τ_E (Eulerian time scale) were measured from various tower locations during the field trials mentioned above (Mickle et al. (1984)). Although the relation between τ_L and τ_E measurements has been found to vary considerably, (Reid, loc. cit.), we use the relation suggested by Hall (1975) for neutral stability, for all our calculations:

$$\tau_L \sim 4.5\,\tau_E$$

The following expressions were then developed:

Neutral, from z_T downwards:

$$\sigma_w(z) = 1.25u_*[0.2+0.8\exp(-(1.2z_T-1.2z)^2/70)]$$

from 1.2 z_T downwards: (29)

$$\tau_L(z) = \tau_L(1.2z_T) \tag{30}$$

Stable, from 1.2 z_T downwards:

$$\sigma_w(z) = 1.25\mu_* \tag{31}$$

$$\tau_L(z) = \tau_L(1.2z_T) \tag{32}$$

Unstable, from 2 z_T to z_0:

$$\sigma_w(z) = \frac{z-z_0}{2z_T-z_0}[1.25u_*(1-4.1\frac{z}{L})^{1/3}] \tag{33}$$

$\tau_L(z)$: Use equation (22) down to 1.2 z_t,
then $\tau_L(z)$ = const below $1.2z_T$ (34)

ii) Droplet Evaporation.

This is treated as adiabatic diffusion from a sphere as described by Picot et al. (1981) for formulations which are complex solutions. Droplet diameters are computed as functions of time after generation and are used to calculate settling velocities.

iii) Foliage Deposition.

When the droplet enters the forest canopy, there is a probability that it will impact on foliage. This probability is the product of (a) the probability that the droplet trajectory will cause it to interact with a foliage element, and (b) the probability that the interaction will result in deposition by inertial impaction. The first of these is equivalent to the foliage cross-section per unit of spatial area through which the droplet is moving, and the second is the impaction collection efficiency for droplets on foliage shoots.

The collection efficiency for the foliage shoots was calculated from a product of the May and Clifford (1967) ribbon collection efficiency and a shelter factor defined as

$$f = a + bv \tag{35}$$

where v is the approach velocity of the droplet in the air stream (m/s). The shelter factor was found by using a foliage simulator originally calibrated in a small wind-tunnel (Picot et al., 1986) and subsequently calibrated against foliage in the field using twigs from various tree species (van Vliet, (1987), Table 2).

TABLE 2: Foliage Calibration and Shelter Factor Constants.

Target	Foliage Calibration Constant (μg tracer/g shoot)/ μg/5 simulators)	Shelter Factor	Species Distribution
Simulator	–	0.39	–
Spruce	0.1033	0.088	48.95%
Jack Pine	0.0918	0.0713	49.11%
Fir	0.133	0.2455	1.94%

Average shelter factor = 0.08

The shelter factor calculated for the simulator is considered valid for the range of droplet sizes (10-50 μm) and approach velocities (< 2 m/sec) to be expected as the droplet cloud is dispersed within the forest canopy.

iv) Forest Stand Characteristics

Data on type and size of trees in the spray plot are needed for the model. For the field trial comparison herein, data was obtained from the NBSERG field trial site near Dunphy, N.B. (van Vliet (loc. cit.)). Species were predominantly spruce (red/black) and jack pine. Foliage area over the 1000 m long test grid varied from 2.64 to 4.01 m^2 of foliage per m^2 of ground. Trees were up to 20 m (66 ft) high with 1/3 of the area from 20 m (66 ft) down to 10 m (33 ft), and the next 1/3 between 10 m (33 ft) and 6.5 m (21.3 ft), on average. Average forest stand values (for density and collection efficiency) and average vertical foliage distribution values were used in the calculations.

3. METHOD OF CALCULATION

Figure 1 and Table 1 show details of the initial conditions specified for the VORTEX WAKE segment, which represent the passage of the spray aircraft over the spray plot in a direction normal to the mean wind vector at aircraft height. (This simulates spraying in a crosswind). The vortex pattern is assumed to be present immediately after passage of the aircraft. Computations were carried out in a 151 by 76 point grid. The initial grid dimensions were allowed to expand with time as the vortices dispersed and descended. A lower limit of the lower boundary of 14 m (46 ft) was applied, where the lower boundary was given a vorticity specified by the gradient in horizontal velocity of the undisturbed atmosphere at z = 14 m (equations (12), (25), (26) and (27)). Initial stepsizes were 0.01 seconds. This was permitted to increase according to the Courant condition (Roache, 1972) during the calculation:

$$\bar{u} \cdot \Delta t/\Delta y \leq 1 \tag{36}$$

The VORTEX WAKE segment calculation was carried on until velocities had decayed to within 5% of the background values specified as atmospheric background values. At each time step, equations (14) were used to calculate droplet displacements from initial location given by the atomizer location on the aircraft wing. The Lagrangian segment was activated as mentioned above. For each atomizer spectrum size class, 4000 droplets were released. The spectrum was divided into 6 droplet size classes and calculations were performed up to 400 m (1312 ft) downwind of the aircraft spray line. Calculations were stopped when 95% of the droplets had either deposited on foliage or ground or been swept beyond the 400 m (1312 ft) point. Deposit and drift data were then constructed for a given atomizer by weighting the specific size classes according to individual atomizer generation spectra.

MODEL PREDICTIONS AND COMPARISON WITH FIELD DATA

TABLE 3 gives the atomizer generation characteristics for the two aircraft used in the Dunphy field trials, from wind tunnel atomizer measurements.

TABLE 3: Droplet Emission Spectra, Dunphy Tests

Size Range μm	Nominal Size μm	Vol. Fraction TBM-TJET	Vol. Fraction AGTRUCK-MICRONAIR
0 - 10 μm	5 μm	.0015	.002
10 - 30 μm	20 μm	.1485	.12
30 - 50 μm	40 μm	.12	.29
50 - 70 μm	60 μm	.19	.19
70 - 90 μm	80 μm	.20	.09
90 - 110 μm	100 μm	.15	.17
110 - 250 μm	180 μm	.19	.138

Table 4 gives the relevant parameters of the Dunphy trials used for simulation calculations.

TABLE 4*: Parameter Listing for Three Spray Scenarios

Parameter	Dunphy Spray Run			
Name	TBM SP#3-84	TBM/AGT SP#2-86	TBM/AGT SP#6-86	TBM/AGT SP#7-86
Date-Time	17-6-84 - 6:57	7-7-86 - 10:35	17-7-86 - 6:44	17-7-86 - 15:56
ATM. Stability	Slightly Unstable	Near Neutral	Very Stable	Unstable
Tracer Emmission(1) (mg/m Flight path)	2030	2165/1032	2061/895	2061/660
Wind Direction (°MAG)	240	252/224	265/265	265/265
Aircraft Speed (m/s)	77.0 (253)	77.0/49 (253/161)	77.0/49 (253/161)	49 (253/161)
Aircraft HT (maGL)	52 (171)	44.5/63.0 (146/207)	36.0/35.1 (118/115)	42.2 (138)
Wind Speed (m/s, ARCFT HT)	4.5 (14.8)	6.6/7.6 (21.7/24.9)	4.2/4.1 (13.8/13.4)	4.3 (14.1)
Relative Humidity (C25mAGL)	50%	78%	82.6%	29.7%
T(°C, 25 m)	10.2 (50)	15.2 (54)	13.3 (56)	28.3 (82.9)
Dθ/DZ (°C/m, POT)	−0.002	−0.004	0.0425	−.0077
R1 (GRT R1#, 25 m)	−0.035	−0.0132	0.0769	−.0511
u* (m/s)	0.35 (1.15)	0.835 (2.74)	0.265 (0.87)	.668 (2.19)
L (m, MO Length)	−340 (−1115)	−833 (−2732)	53 (174)	−175 (−574)
TMIXL (m)	80 (262)	450 (1476)	250 (820)	>1000

* Dunphy meteorological data from R.S. Crabbe, N.A.E., Ottawa; R.B.B. Dickinson, Forestry Faculty, UNB Fredericton, and R.E. Mickel, A.E.S. Downsview. Deposit data from C. Wiesner, N.B.R.P.C. Fredericton and S. van Vliet, UNB Chem. Eng. Dept. Fredericton (loc. cit.). Data found elsewhere in this proceedings.

The formulations used in both cases are given in TABLE 5. In both cases these are emulsions with water as the continuous phase. Experiments on single evaporating droplets have shown (Holder, (1979)), that in such a case, evaporation of the water phase occurs as though the droplet were pure water, down to the point where essentially all of the water has evaporated (the droplet reaches a final diameter equal to 55% of its original diameter unless it deposits before it is fully evaporated).

TABLE 5: Dunphy Spray Trial Formulations

TBM Formulation Component	(Teejet 11010 Atomizer) Volume %
dibutyl phthalate	9.3
tris-2-ethylhexyl-phosphate	2.6
atlox	2.6
dowanol	2.6
water (including 0.75% mass rhodamine B dye)	82.9

AGTRUCK Formulation Component	(AU4000 Micronair Atomizer Volume %
dibutyl phthalate	2.3
triphenyl phosphate	2.3
dowanol	2.5
atlox	9.2
Erioglaucine A100 dye	0.5
water	83.2

TABLE 6 shows a comparison between experimental and computed total canopy deposits, (from spray line to 400 m downwind) total ground deposits (same zone) and total drift beyond 400 m downwind for the Dunphy spray trials mentioned above.

TABLE 6: Computed and Experimental Deposit and Drift

TBM	% on Canopy	% on Ground	% Drift
Run 2-86	14.3 (24.9)	1.1 (4.7)	42.1 (70.4)
Run 6-86	14.9 (25.1)	10.7 (26.6)	46.2 (48.3)
Run 3-84*	8.2 (23.5)	3.8 (8.6)	47.7 (67.9)
AGTRUCK			
Run 2-86	6.7 (9.0)	0.4 (1.7)	59.1 (89.3)
Run 6-86	17.6 (26.2)	9.7 (17.4)	90 (56.4)
Run 7-86*	18.6 (24.5)	1.8 (7.0)	— (68.5)

Notes
1. Bracketted values are from model.
2. Experimental values for % Can + % Gnd + % Drift do not add to 100% due to unavoidable experimental errors.

* Since time of writing, the numerical model for the unstable case has been modified. Refer to note in proof.

Agreement between model and experiment is generally very good for this type of calculation. No attempt is made here to further "calibrate" the model, even though canopy deposit predictions are systematically high for the TBM. In the theoretical calculation of foliage deposit, all foliage is considered to be equally accessible, no allowance being made for the downwind side of the tree being somewhat sheltered from the spray cloud. Figure 2 and 3 show predicted and measured foliage deposits versus downwind position for the #2-86 Dunphy trial (for neutral atmospheric conditions, relatively high wind speeds of about 7 m/s (23 ft/s)).

Computed peak deposits are seen to occur at approximately the same locations as for experimental peak deposits. The difference in the location of this peak for TBM and AGTRUCK aircraft is attributable to the large difference in spray eight (44.5 m (145 ft) for TBM 63.0 m (207 ft) for the AGTRUCK.

In the case of Figures 4 and 5 for very stable conditions, peak deposits appear much closer to the sprayline (due to lower wind speed and lower aircraft height) with the AGTRUCK having a slightly greater canopy deposit and a slightly lower aircraft height.

In all the above figures, the experimental data shows a considerable degree of irregularity. This is attributed to non-uniformity in tree density, the test plot being a naturally regenerated cut-over area approximately 40 years old. Experiments were done with five alternating sets of spray passes for each aircraft.

A parametric evaluation of wind speed, aircraft height, and type of aircraft is shown in TABLE 7 based on computer runs with spray run 2-86 as reference.

TABLE 7: Computed effect of varying height and wind speed (Dunphy 2-86 conditions)

Params	Run No.	1	2	3	4	5	6
u_*		0.84	0.2	0.84	0.2	0.84	0.84
$\bar{u}$		6.6	1.6	6.6	1.6	5.4	5.4
Sprayh		44.5	44.5	44.5	44.5	30.0	30.0
% Gnd Dep		4.7	17.8	4.4	17.3	6.73	6.5
% Can Dep		24.9	26.3	23.7	24.6	41.3	39.3
% Drift		70.4	55.8	71.9	58.0	52.0	54.2

NOTES: 1) $\bar{u}$ is at SPRAYH (Spray Height).
2) Runs 1, 2, 5 are TBM runs, runs 3, 4 6 are AGTRUCK runs.

The TABLE 7 results indicate that

1) The TBM aircraft gives a higher canopy deposit than the AGTRUCK under the same conditions.

2) Higher windspeed decreases canopy deposit slightly for both the TBM and the AGTRUCK under neutral conditions.

3) Aircraft height is the most important factor, the canopy deposit for both the TBM and the AGTRUCK increasing 66% with height reduction from 44.5 m (146 ft) to 30 m (98 ft) above ground level. The 30 m height was the lowest value recorded for aircraft height (TBM) in the Dunphy field trials. Lower flying heights are not feasible for the Dunphy forest stand where some trees reach 20 m (66 ft) in height.

The Dunphy field trials do indicate that aircraft height is the most important factor in determining foliage deposition (van Vliet, loc. cit.).

Table 8 shows a calculated comparison of foliage and ground deposits for the TBM aircraft under different atmospheric stability situations using constant spray height and a constant windspeed at spray height (4.1 m/s), using the Dunphy 6-86 field trial condition as reference.

TABLE 8: Computed Effect of Stability Class (TBM Dunphy 6-86 Conditions as Reference)

Stability	% on Canopy	% on Ground	% Drift
Very Stable (L = 53 m)	25.1	26.6	48.2
Neutral (L = ∞)	34.7	9.7	55.3
Unstable (L = −53 m)	57.9	0.2	41.9

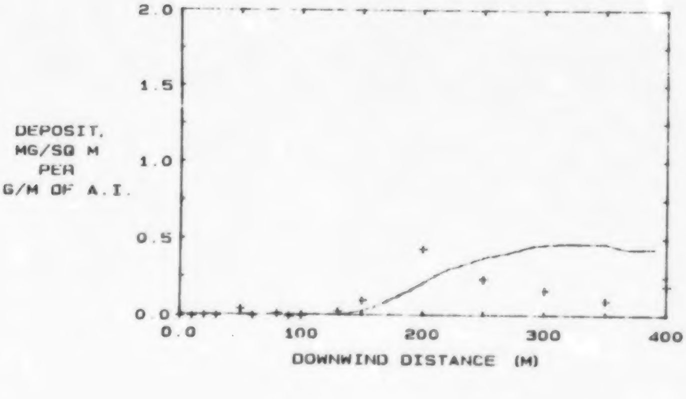

FIGURE 2: CANOPY DEPOSIT VS DISTANCE FOR TRIAL 2-86. AGTRUCK
+ EXPT'L DATA ______ COMP'D DATA

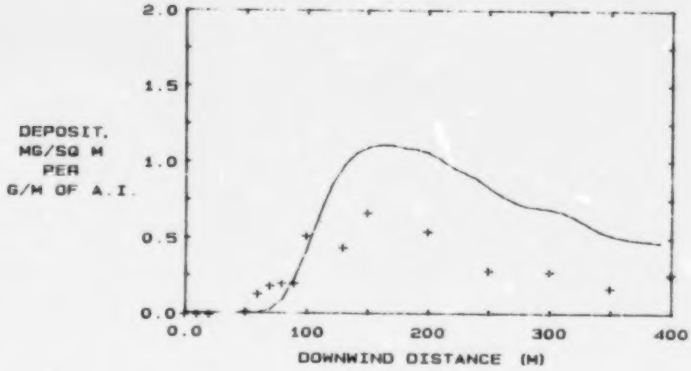

FIGURE 3: CANOPY DEPOSIT VS DISTANCE FOR TRIAL 2-86. TBM
+ EXPT'L DATA ______ COMP'D DATA

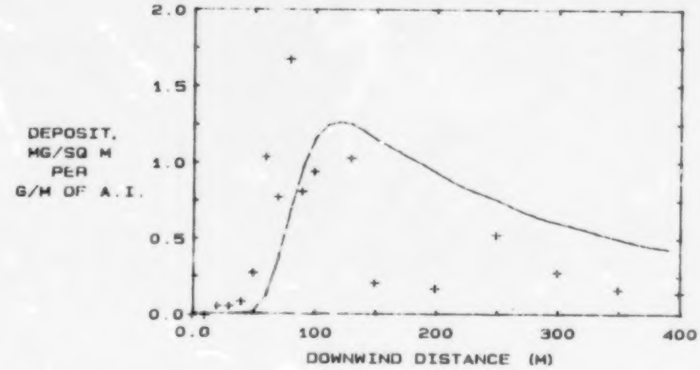

FIGURE 4: CANOPY DEPOSIT VS DISTANCE FOR TRIAL 6-86. AGTRUCK
+ EXPT'L DATA ______ COMP'D DATA

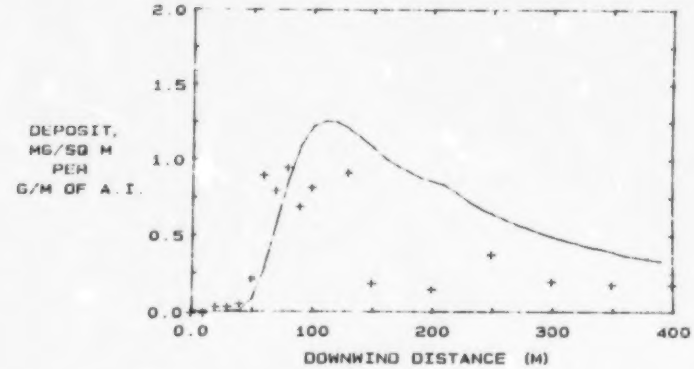

FIGURE 5: CANOPY DEPOSIT VS DISTANCE FOR TRIAL 6-86. TBM
+ EXPT'L DATA ______ COMP'D DATA

The Table 8 results show a pronounced reduction in ground deposit (well demonstrated in the field trial data of Table 6, going from the very stable to the unstable situation with maximum canopy deposit showing up in the unstable case. Increased vertical motion of turbulent eddies under unstable conditions provides the optimum situation for maximizing canopy deposit. These conditions occur shortly after sunrise when thermal heating of the trees quickly creates an unstable zone at low altitude.

CONCLUSIONS

The PKBW model gives very good results for prediction of droplet deposition on coniferous foliage and ground for the best terrain considered here where tree cover is predominantly coniferous. It is currently being used to carry out computer investigations of the affects of operational modifications in forestry spraying by the New Brunswick Spray Efficacy Research Group. The obvious importance of aircraft height has been recognized. However, aircraft vortex strength is shown to be important. Higher strengths permit the droplet cloud to be projected into the canopy before significant dispersion. Optimization of aircraft type and aircraft operation then becomes possible. Plans for testing heavier fixed-wing aircraft and helicopters are under way. Preliminary tests will be done with the PKBW model, followed by field trials. The objective is increased foliage deposit and reduced off-target drift. Significant improvements seem possible.

ACKNOWLEDGEMENT

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Note in Proof

1) Modification of the model for the unstable case has led to appreciably different results. The model has not been rerun with the modified version for the unstable scenarios listed in Table 4, however, reruns for other studies involving unstable conditions have indicated that in general, canopy deposit is increased by approximately 100%, ground deposit is negligible, and drift is reduced.

2) The model is not well behaved under unstable conditions: there is an artificial bias for material to drift downward into the canopy. Thus, predictions in canopy deposit may be artificially high.

In this respect, improvement in the model is required.

CALCULATION OF AEROSOL DISTRIBUTIONS IN AERIAL SPRAYING OF FORESTED TERRAIN

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ABSTRACT — A mathematical model developed for the analysis of the time history of sprays emitted from an aircraft in close proximity to the ground is adapted here to forest spraying. The model calculates the wake formed by the aircraft, including the roll-up and development of concentrated vorticity. The deformed wake motions are affected by ambient wind and the induced flow on the ground, including the vegetation shape and density. The droplets are assumed to drift, relative to the flow field at speeds varying from the injection speed to a terminal, creeping velocity. At the same time evaporation is accounted for resulting in droplet size diminution. Predictions of the model are compared to the Dunphy tests, showing qualitative agreement. The amount of spray material arriving at ground level is found to be overestimated as a result of uncertainties in evaporation rate data for multicomponent solutions.

RÉSUMÉ — Un modèle mathématique mis au point pour l'analyse de l'évolution dans le temps des aérosols pulvérisés à partir d'un aéronef très près du sol est adapté ici à la pulvérisation des forêts. Le modèle calcule le sillage formé par l'aéronef, y compris la formation et le développement d'un tourbillon concentré. Les mouvements déformés dans le sillage sont perturbés par le vent ambiant et par l'écoulement induit sur le sol, ce qui comprend la forme et la densité de la végétation. On suppose que les gouttelettes dérivent par rapport au champ d'écoulement à des vitesses allant de la vitesse d'injection à une vitesse terminale de fluage. En même temps, l'évaporation qui fait diminuer la taille des gouttelettes est prise en compte. Les prévisions du modèle sont comparées aux essais de Dunphy, et la comparaison indique un accord qualitatif. La quantité de matière pulvérisée qui arrive au sol est surestimée à cause d'incertitudes dans les données sur le taux d'évaporation pour des solutions à plusieurs constituants.

INTRODUCTION

Aerial agricultural spraying has been developed from being an art performed by daredevil pilots using hard earned experience and empirical results into a scientific discipline, with a growing dependence on simulations and predictive methods. While these are still far from being quantatively accurate many qualitative features can now be predicted, and the beginnings of technological optimization are possible. The Department of Aeronautical Engineering at Technion has been running a multi-disciplinary program studying advanced methods in agricultural aviation. This includes special avionic aids for safer low-altitude flying, sizing and structural design studies, and the work that resulted in the present paper — on the analysis of low-level aerial spraying.

A mathematical model analysing the flow field around low flying aircraft (Fig. 1), and the interactions of this flow field with the ejected spray droplets was developed and applied to problems of spraying flat fields from altitudes of order of magnitude of the wing span (Atias and Weihs, 1984, 1985 — hereafter referred to as AW1 and AW2, respectively). In the present paper, this model is applied to spraying in forestry situations, which cause several major changes. First, the aircraft usually flies at much higher altitudes, causing many of the effects studied in detail in the papers mentioned above to be much less important. These include ground-caused distortion of the aircraft wake and its influence on wake rollup and the trajectory of the droplets, as well as effect of the plant cover density. On the other hand, effects, which were neglected previously in our model gain significance here and have been added. These include the presence of side winds, the influence of the ground surface not being flat (simulation of tree-cover), the larger time scales involved in spraying from higher altitudes, and details of the evaporation process in solutions.

The results presented here are of two categories. First, the effects of sidewinds, and the presence of a bumpy surface (modelling the presence of trees) on the development of the wake are examined. A second, a comparison to some of the results of the Dunphy 1986 tests (Van Vliet, 1986, Crabbe pers comm.) is presented.

THE MODEL

The model used starts off with a description of the flow field around the aircraft which is assumed to consist of a flying wing only. This assumption results in two types of errors which are neglected here, first the fuselage and tail effects having a symmetrical disturbing influence, and second, the asymmetric, swirling component introduced by the propeller wake. The tail wake is usually not more than 10% in strength and 25% in span of the wing wake, while the propeller and fuselage wakes interact (at least for single engine planes) to reduce their influence, so that their neglect does not cause large errors.

The wing wake is modeled by a series of line vortices of strength defined by the lift distribution (assumed elliptical). Each vortex has a viscous core — modeled as a circular zone of solid-body rotation (Phillips, 1981). Each vortex is assimilated into

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the tip vortex after one full rotation around the tip vortex (Moore, 1974), strengthening it. The ground surface boundary layer flow is described by vortex sheet elements similar to those used by Chorin (1978). These elements, upon separation are turned into vortex filaments, again with a linear core. This model is more fully described in AW-1 where its advantages over finite difference schemes, in terms of enabling realistic Reynolds numbers, are detailed. Tree cover is approximately modeled here by taking the aircraft to fly parallel to tree rows, so that the trees can be modeled by waviness of the ground surface. A more complicated three-dimensional model, based on doubly-harmonic (elliptic) functions is presently under consideration, but is not yet in final form. Here, the tree rows are schematically shown as half-circular cylinders (Fig. 2). The effects on the flow field, and wake vortices are calculated by successive use of the circle theorem (Milne Thomson, 1968). The deformation in the circular contours due to neighboring circles is not taken into account primarily because tree contours are not circular in the first place, and the distortion can be compared to pressure field effects on the leaf profile. When the cylinders are more than two tree contour radii apart, the difference is less than 5% anyway.

Ground boundary layer effects are analysed as in the flat ground case, with the added proviso that separation occurs at the top of each tree profile (see Fig. 3). While better estimates for the separation point are available for circular contours, these were not used here as trees are usually vertically elongated so that separation is forced closer to the zenith.

Finally sidewind effects are included by adding a combination of shear flow and uniform flow in the spanwise direction. The shear flow which was used in all calculations is based on atmospheric boundary layer models. The main effect of side winds is to strengthen one wing vortex and unravel the other, in addition to the intuitively obvious sideways shift of the wake as a whole.

Once the continuum flow model is established, we add the spray droplets. These are added to the flow field at a finite number of points along the span, usually at, or near to, the wing trailing edge. The mass flow rates and initial droplet size and the initial velocity vector relative to the point of injection are input parameters. An unsteady Stokes flow model is used for the drag on the individual droplets. The fact that aerial sprays are usually Ultra Low Volume (Lawson and Uk, 1978) is utilized to neglect interaction between neighboring droplets and any possible effects of the spray on the aerodynamic flow field. The droplets slow down due to the drag, keeping a spherical shape at all times. For droplets of the size range typical for aerial spraying (50–300μ) deformations from the spherical shape start only for $Re=0(10^3)$ based on drop diameter — i.e. far above the speeds obtained here.

The droplet motion is calculated taking into account gravity, aerodynamic drag and evaporation. The equations of motion are (AW-2)

$$F_x = - F_D \frac{u}{V_r} \qquad (1)$$

$$F_y = - F_D \frac{v}{V_r} - \frac{4}{3} \varrho_d \pi r_d^3 g \qquad (2)$$

where

$$F_D = \frac{1}{2} \varrho_a V_r^2 \pi r_d^2 C_D \qquad (3)$$

and

$$C_D = \frac{24}{Re} (1+0.1\ Re^{0.75}) \qquad (4)$$

The calculation is of quasi-steady marching type, where the drop velocity and radius is taken at each step, and its position is calculated from the previous step velocity. The drop radius changes due to evaporation. This is modeled by defining (as inputs) atmospheric temperature and relative humidity, as well as initial drop temperature. The drops are taken to be pure water in the present calculation. Obviously aqueous solutions, or other liquids may be substituted provided the thermochemical data is available for them.

In a previous study (AW-2) it was shown that the drop temperature reaches local wet-bulb temperature extremely quickly, so that for most of the process the temperature stays fixed. Mass transfer between the droplet and surroundings includes diffusion and evaporation.

RESULTS

We present two sets of results in this report. First, some theoretical examples of the effects of side winds, and ground contour shape on the flow field behind and underneath the spraying aircraft. After that, some results based on the data of the Dunphy (1986) experiments, for comparison purposes will be shown.

In previous studies (AW-1, AW-2) the vortex wake was assumed to have rolled up very rapidly relative to the time scale required for the drops to reach the ground. This is probably correct for relatively high altitude flying but needs to be checked for lower altitude release of spray. Figure 4 shows the trajectory of the wing tip vortex for 3 initial heights a function of nondimensional time $t^* = \frac{t\Gamma_o}{x_o^2}$, and compares it to the motion of the centroid of vorticity of a sheet wake in the process of rolling up. Obviously, for smaller initial heights the differences are larger, but we see that the qualitative behavior of both sets of trajectories is similar. In both cases, the secondary vorticity caused by the ground boundary layer results in a late rise in the centroid trajectory. However, because of the more diffuse nature of both the wake and ground vorticity, this rebounding effect is reduced.

Next, the effect of side winds is examined. When uniform (in terms of vertical distribution) side winds were added to the input data, no significant changes, except for the expected sideways shift of the wake, were obtained. A vertical shear profile, typical of the atmospheric boundary layer was introduced. This too had a side wind of 1.2 m/s at 5 m altitude ($U_w^*=2$). Figure 5 shows the shape of the vortex wake at a nondimensional time of $t^*= 1$. The left half, where the vorticity is of the same sign as that of the windshear, is more tightly rolled up and stronger. Also, the centroid of vorticity on the windward side has moved less (because of the countering effect of the ground boundary layer). Similar results of uneven unravelling were observed experimentally (Tombach, 1971) and obtained by Bilanin et al. (1978) for concentrated vortices, but the wind effect on the roll up process has not been analyzed previously. The roll up rate differs between the two vortices, the windward one collecting 98% of the total vorticity at time $t^*=1$ vs. 83% for the lee vortex, and 92% for both in the case of no side wind (see Fig. 6).

As mentioned in the Introduction trees were modeled roughly by a series of semicircular cylinders spaced regularly in the spanwise direction. These model rows of trees in the direction of flight. Figure 7 shows the trajectory of the vorticity centroid (now in the absence of side wind) for vorticity at an initial height of 1 and

2 tree heights, respectively. The rebounding effect is accentuated and accelerated because of the separation occurring at a fixed point, concentrating the secondary vorticity (Fig. 3). The contour effect presented in Figs. 7 and 3 exaggerates the importance of this contribution to the flow field as actual trees allow some through flow, which results in spreading of the shed secondary vorticity.

Comparison with the Dunphy results

The second part of the results obtained in the present study includes a partial comparison to the Dunphy 1986 spray trials, as summarized by Van Vliet, (1986), with amendments in private communications from Picot, dated December 19, 1986 and January 6, 1987.

The data and results were presented in a very good and concise manner in the references cited above. However, some of the input data required for the program were missing and we had to assume values for these. As a result, the comparison can really be only qualitative, and in that sense gives relatively good agreement.

For example, lacking more detailed information, we assumed that the mass flow rate from all nozzles is uniform. This is a critical assumption as one can show that the mass flow rate distribution is one of the most sensitive parameters, and by choosing specific distributions the peakiness in the mass deposition function can be shifted, increased and reduced.

Also, the drop size data was given in 20μ size groups for radii up to 100μ, but no data was given between 100-180μ.

The experimental data were applied in the following fashion:

i) Droplet size distribution was taken from Picot (1987, private communications) mentioned above. A separate run was performed for each size group and ground deposition was then summed up.

ii) Temperature and relative humidity were taken from the data printout at the 390 m station — which was the closest to the solution area. The temperature and humidity were assumed constant, and wind strength is altitude-dependent.

iii) The droplets were "stopped" at the canopy height, which from Table 1 accompanying the data of Picot (December, 1986) was about 14 m for 0.5 cumulative foliage fraction. This value seems somewhat high and needs probably to be reduced. We did not calculate penetration of the vortex and droplets into the tree-cover.

iv) Evaporation was halted when the instantaneous diameter was 50% of the initial droplet diameter. This simulates drops with 12.5% non-volatiles by volume (Reid and Crabbe, 1980).

We ran comparisons with the Dunphy Cessna 188 runs no. 2,4,6,7 and 10. These appear as Figs. 8-12. The abscissa in these figures is a nondimensional spanwise distance from the airplane centerline with unit length taken as the Betz distance of the wingtip vortex from the wing root. For the present case the length unit is $\approx \frac{12.7}{2} 0.8 \approx 5$ m. The ordinate shows the percentage of original spray volume deposited per spanwise section of one length unit (≈ 5 m) each. This includes the remaining water (in cases where the final volume was more than the 12.5% non-volatile fraction assumed).

We did not add the experimental results of Van Vliet (1986) to Figs. 8-11 as they were presented as either canopy or ground results, while ours are close to — but not exactly the total results. Also, experimental graphs were later corrected (Van Vliet, 1986 App. E). There is qualitative agreement between measurements and results, these being seen best by integral quantities such as the total percentage of spray reaching the ground (Table 1), or geometrical position (Table 2).

TABLE 1: Comparison of present calculated results with experimental data of the Dunphy tests, Van Vliet (1986). The asterisk indicates full water evaporation.

Spray No.	Present Results	Dunphy App. E (corrected)	Dunphy (from figures)
2	12.5*	10.3	12.3
4	19.9	26.7	28.2
6	24.8	38.9	39.9
7	12.5*	24.7	26.0
10	12.5*	20.4	22.6

From Table 1, we see that our results showed consistently higher evaporation than the experiments. The corrected data shows somewhat better agreement, but the differences are still large enough to indicate some mechanism not being accounted for in the numerical model. The most likely candidate is the evaporation rate, which in real drops is probably affected by the presence of surfactants and the solutes themselves. We are planning on adding this effect to the model in the future. However, any improvement in results due to this correction is fortuitous to some degree, as empirical results are required for the evaporation-retardation rate, i.e. there will always remain an element of curve-fitting.

The numerical results had the same relative behavior, i.e. when the experimental percentage was higher, so was the numerical calculation.

TABLE 2: Positions of Peak deposition in meters from flight centerline.

	Present	Results	Dunphy	Experiments
Spray No.	Inner Peak	Outer Peak	Inner Peak	Outer Peak
2	190	415	205	440
4	25	80	60	125
6	25	85	75	125
7		150		160
10	55	100	50	120

The placing of peak deposition is consistently further out in the experimental data, but the differences are not very large. One reason for the differences could be the fact that we did not have a good estimate for drop size distribution around 180μ. Bigger drops tend to fall closer to the vertical, and thus the lateral spacing is reduced.

CONCLUSIONS

The numerical model presented gives qualitative agreement with existing experimental data. However, it seems difficult to improve the quantitative fit, due to various physical mechanisms for which not enough data is available. These include evaporation rate, and wind shear. Thus our model is better suited to its original purpose of low level spraying, as it treats the wake and drop trajectory in more accurate manner than evaporation (which becomes dominant after the long residence times encountered in forest spraying).

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NOMENCLATURE

C_D — Drag coefficient
F — Force
g — Gravity acceleration
r — Drop radius
Re — Reynolds number based on drop diameter
u,v — Velocity components in the x,y directions, respectively
U — Aircraft speed
V_r — Relative velocity between droplet and surroundings
t — Time
t^* — Nondimensional time
x — Length coordinate in the spanwise direction
y — Length coordinate the vertical direction
x_o — 80% of wing semispan
Γ_o — Aircraft lift vortex = (weight of aircraft) / $\varrho_a(2x_o)U$
ϱ — Density

Subscripts

a — Ambient air
d — Drop

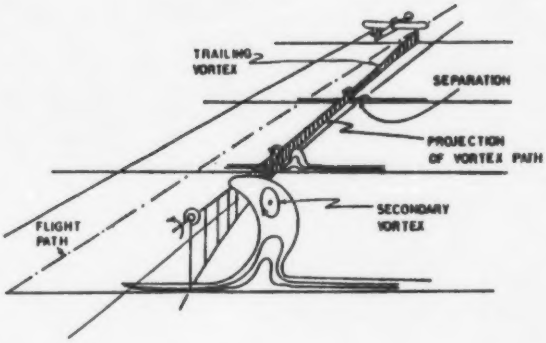

FIGURE 1: SCHEMATIC DESCRIPTION OF THE AIRCRAFT WAKE MOTION.

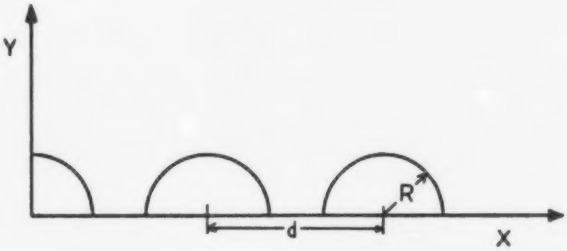

FIGURE 2: SCHEMATIC DESCRIPTION OF UNDULATING GROUND.

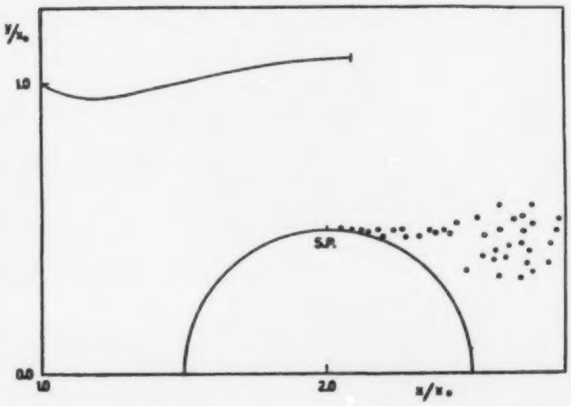

FIGURE 3: TRAJECTORY OF CENTROID OF VORTICITY SHED FROM A WING PRODUCING LIFT OF 10,000N MOVING HORIZONTALLY AT 30M/S, AT HEIGHT 20 M (2 TREEHEIGHTS) (FULL LINE), AND THE VORTICITY SHED FROM A SEMI-CIRCULAR TREE ROW. S.P. STANDS FOR SEPARATION POINTS.

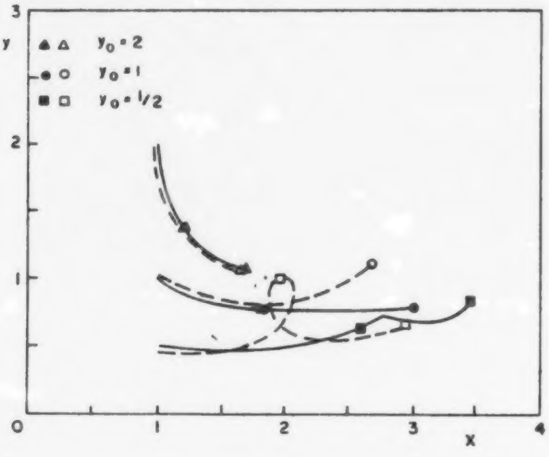

FIGURE 4: TRAJECTORY OF THE CENTROID OF VORTICITY OF AN ELLIPTICALLY LOADED WING FOR VARIOUS NONDIMENSIONAL INITIAL HEIGHTS y. Δ,o,+ REPRESENT VORTEX CENTER POSITIONS AT NONDIMENSIONAL TIMES t* = 2 AND 4 FOR DIFFERENT INITIAL HEIGHTS (THE FULL LINES). DASHED LINES INDICATE TRAJECTORIES ASSUMING ROLL UP TAKES PLACE INSTANTANEOUSLY.

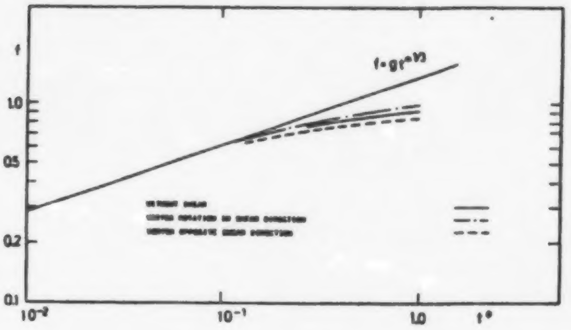

FIGURE 6: FRACTION OF ROLLED UP VORTICITY AS A FUNCTION OF TIME ON THE TWO SIDES OF THE WING, IN SHEAR FLOW.

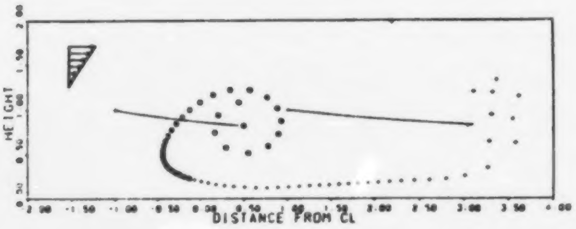

FIGURE 5: SHAPE OF VORTEX SHEET ROLLING UP BEHIND AN ELLIPTICALLY LOADED WING IN GROUND EFFECT, AT t* = 1.0, FOR SIDE SHEAR WIND CHANGING LINEARLY FROM VELOCITY $u_\infty^* = 2.0$ AT FLIGHT ALTITUDE ($y_0 = 1.0$) TO ZERO NEAR THE GROUND. FOR WING LOADING SEE FIG. 3.

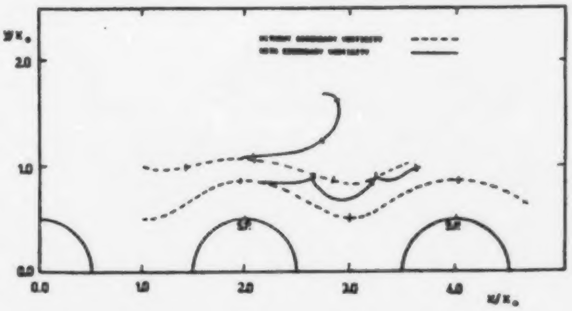

FIGURE 7: VORTEX TRAJECTORY IN THE PRESENCE OF UNDULATING GROUND WITH AND WITHOUT SECONDARY VORTICITY. + REPRESENTS THE LOCATION OF THE VORTEX CENTER AT EACH t* = 1.0.

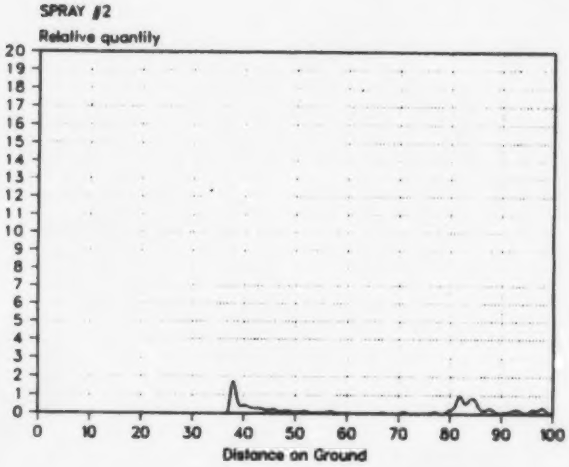

FIGURE 8: DISTRIBUTION OF SPRAY MATERIAL AT CANOPY HEIGHT AS A FUNCTION OF NONDIMENSIONAL LATERAL DISTANCE FROM FLIGHT CENTERLINE. THE ORDINATE INDICATES PERCENTAGE OF INITIAL SPRAY MASS DEPOSITED. DATA FROM CESSNA 188 RUN NO. 2. (VAN VLIET, 1986).

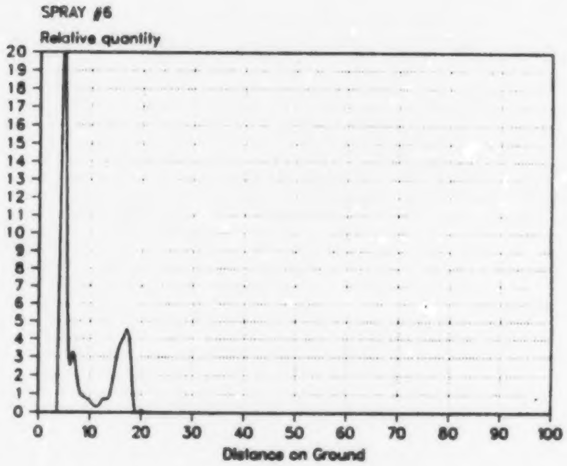

FIGURE 10: DISTRIBUTION OF SPRAY MATERIAL AT CANOPY HEIGHT AS A FUNCTION OF NONDIMENSIONAL LATERAL DISTANCE FROM FLIGHT CENTERLINE. THE ORDINATE INDICATES PERCENTAGE OF INITIAL SPRAY MASS DEPOSITED. DATA FROM CESSNA 188 RUN NO. 6. (VAN VLIET, 1986.)

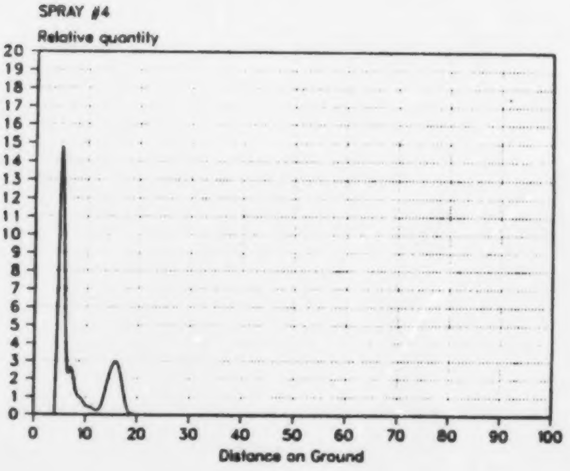

FIGURE 9: DISTRIBUTION OF SPRAY MATERIAL AT CANOPY HEIGHT AS A FUNCTION OF NONDIMENSIONAL LATERAL DISTANCE FROM FLIGHT CENTERLINE. THE ORDINATE INDICATES PERCENTAGE OF INITIAL SPRAY MASS DEPOSITED. DATA FROM CESSNA 188 RUN NO. 4. (VAN VLIET, 1986).

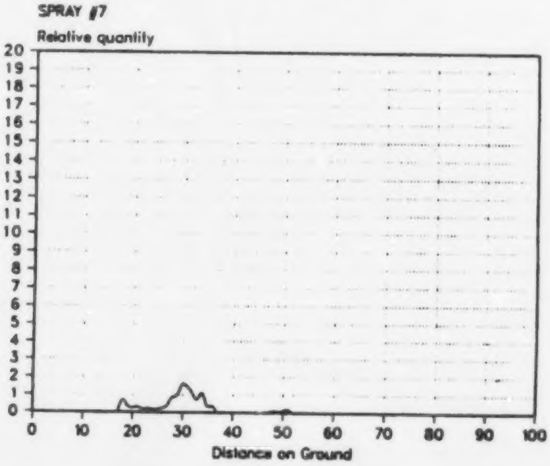

FIGURE 11: DISTRIBUTION OF SPRAY MATERIAL AT CANOPY HEIGHT AS A FUNCTION OF NONDIMENSIONAL LATERAL DISTANCE FROM FLIGHT CENTERLINE. THE ORDINATE INDICATES PERCENTAGE OF INITIAL SPRAY MASS DEPOSITED. DATA FROM CESSNA 188 RUN NO. 7. (VAN VLIET, 1986.)

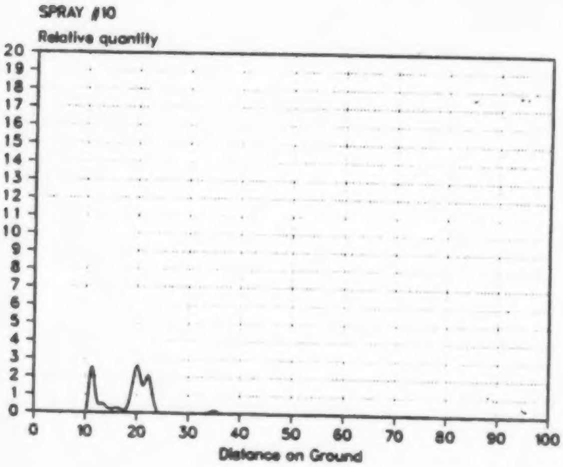

FIGURE 12: DISTRIBUTION OF SPRAY MATERIAL AT CANOPY HEIGHT AS A FUNCTION OF NONDIMENSIONAL LATERAL DISTANCE FROM FLIGHT CENTERLINE. THE ORDINATE INDICATES PERCENTAGE OF INITIAL SPRAY MASS DEPOSITED. DATA FROM CESSNA 188 RUN NO. 10. (VAN VLIET, 1986.)

A REVIEW OF MODELS FOR ULV SPRAYING SCENARIOS

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ABSTRACT — Four models used in the prediction of deposit and drift from aerial application are reviewed in terms of their strengths and weaknesses as related to ULV pesticide spraying. Direct comparisons between models are addressed to assess the effects of operational parameters on near-field deposition patterns and off-target drift. Finally, selected model results are compared with the spray results of the 1984/1986 Dunphy field program.

RÉSUMÉ — Quatre modèles utilisés dans la prédiction du dépôt et de la dérive de l'application aérienne sont revus en terme de leur points forts et faibles par rapport à la pulvérisation à très faible volume (ULV) des pesticides. Les effets des paramètres opérationnels sur les patrons de dépôt à l'intérieur de la region cible et sur la derive hors cible sont étudiés par des comparisons entre les modèles. Finalement, quelques résultats des modèles sont comparés avec ceux du programme de pulvérisation effectuée à Dunphy entre 1984 et 1986.

INTRODUCTION

The means by which spray reaches a target area after release from an aerial application is very complex with a number of variables influencing the ultimate deposit or drift. A complete understanding of the relative importance of each factor on the deposit is becoming increasingly more crucial as the tendency for insecticide spraying is to smaller and smaller droplets, a situation with increased potential for drift. The DESIRE in spraying is to target the entire spray to the area of concern. The REALITY is that a fraction and often a sizeable fraction of the spray drifts to off-target locations. The GOAL, therefore, is to minimize the environmental insult to the non-target areas to a tolerable level through the regulation of buffer zones. However, buffers should not be unnecessarily large because this could possibly impede efficient forest management. The ROLE of models is to provide a tool to operators whereby informed decisions can be made on appropriate conditions to optimize target coverage. Regulators, on the other hand, can utilize these same models to predict off-target deposit from operational sprays under worst-case scenarios and thereby set buffer zones to ensure environmental protection.

An independent review (Concord Scientific, 1987, SENES 1984) of models addressing the aerial spray scenario found in access of twenty models in the literature which focussed on spray deposit. Of these models, four in particular were identified as being superior:

1. AGDISP (*AG*ricultural *DISP*ersion Model; Bilanin et al, 1987, Teske, 1986, Bilanin and Teske, 1984, Bilanin et al, 1978).
2. Weihs — Atias Model (Weihs and Atias, 1987, Atias and Weihs, 1985, and 1984).
3. FSCBG (*F*orestry *S*ervice, *C*ramer, *B*arry, *G*rim; Geary, et al., 1987, Dumbauld et al., 1980).
4. PKBW (*P*icot, *K*ristmanson, *B*asak-Brown, *W*allace; Picot, et al., 1987 and 1986).

In reviewing these models, emphasis is placed on their modelling capabilities for the potential drift component of sprays, ie. for small droplets less than 100 microns.

MAPPING OF SPRAY DRIFT

The complex nature by which spray moves from the spray aircraft to the ground can now be viewed by the use of an ARAL (AES Rapid Acquisition LIDAR) system. The major components of the cloud mapper are a Nd-YAG laser and a 14 inch Celestron receiving telescope which are scanned through a preset angle under the computer control of a COMPAQ 286. By firing short (10 nanosecond) pulses of infrared light from the laser through the spray cloud and monitoring the light which bounces back off the spray droplets in the air, the range of the cloud can be determined from the time of flight of light out and back while a measure of the total cross-section (droplet density × cross-section) can be obtained from the amount of light returned. The horizontal and vertical resolution is typically 1.5 × 1.5 metres at 1 kilometre downrange. From the return of a single shot (Figure 1), detailed information can be obtained on the relative emission from the atomizers of each

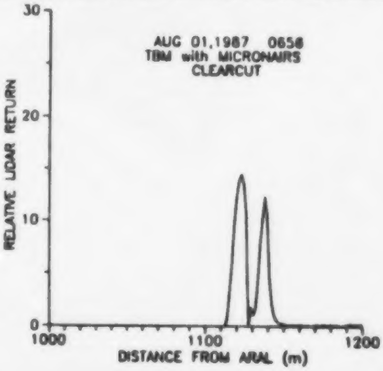

FIGURE 1: RETURN FOR A SINGLE LIDAR SHOT THROUGH THE TBM SPRAY CLOUD

wing and the distribution of material in the spray cloud along the laser path. The laser system is fired at 10 times per second as the assembly is scanned through the spray cloud. Spray cloud sampling is completed in 1 second with an update on the full cloud density every six seconds. By mapping the cloud continuously after the passage of the aircraft, the transport and dispersion of the spray cloud from the aircraft to the target can be followed.

Figure 2, shows the results of the mapping of a TBM with Micronairs* spraying at 25 m over a clear cut area in cross winds of 1.7 m/s blowing away from the ARAL system. For this early morning (0656 EST) spray in a stable surface layer, the ambient temperature was 9.7°C with a relative humidity of 86%. The cloud has been mapped in terms of return signal strength which relates to droplet density. Within the spray release zone (3 seconds), the material is emitted with a particular emission droplet spectrum controlled by the nozzle design, a particular spray formulation giving the volatile to non-volatile fraction and at a prescribed source strength. By 9 seconds, the spray is entrained into the aircraft induced vortices which act as efficient pesticide carriers (9–33 seconds) to move the spray cloud from the aircraft height closer to the target, thus affecting the final deposit given a particular flight line or pattern. As the vortices sink towards the surface, turbulence and cross-wind shear act to selectively break down one (15–21 seconds) or both vortices. In this case, the upwind vortex persists carrying material to the surface while the downwind vortex breaks down releasing the pesticide. When vortex breakdown occurs, large quantities of pesticide can be dispersed (21–39 seconds) at an effective release height with the potential to contribute significantly to off target drift. Vertical mixing can move spray material significantly above the original spray height (63 seconds). Between the release height and impaction zone, the droplets undergo evaporation due to the temperature and humidity of the surrounding atmosphere, thereby reducing their size and making them more susceptable to turbulent dispersion and ultimate drift. Capping inversions restrict the vertical extent of mixing by confining the spray cloud to a channel above the canopy. Within the canopy, changes in the wind speed and turbulence profiles, forest density, tree species, tree height, all interact to produce the canopy and ground deposition at various locations downwind of the spray line.

MODEL REVIEW

Each of the four models incorporated various components of the overall release, dispersion and deposition processes important to spray fate.

(1) AGDISP

The strength of the AGDISP Mod 4.0 model is the detailed treatment of the wake vortex and subsequent entrainment of the spray material. However, a decay factor for the vortices has to be input in order to model decay due to atmospheric turbulence. The authors recommend a value between 1.8 and 0.4 depending on whether the vortices are in or out of ground effect. Cross-wind shear which can selectively destroy the downwind vortex is not modelled.

The turbulence modelling scheme with second-order closure leads to small integration steps (less than 5 milliseconds in real time for sub-60 micron drops) to obtain stable solutions to the equations of motion. The subsequent computer time requirement precluded the use of this model for these smaller droplets (comprising 60% of the emitted mass). Turbulence causes growth of the standard deviation of the released droplets around the mean trajectory from the atomizers until surface deposition. The mean trajectory is modified due to evaporation of the droplet until a lower limit cutoff is reached. The wind and turbulence profiles are applicable to a neutral atmosphere with no capping inversion. In AGDISP MOD 4.0, no canopy module is available. Deposition to a surface is Gaussian in nature centred on the location of impact of the mean trajectory with a standard deviation equal to the spread just before impact. In this form, no allowance is made for continuous deposition due to the oblique angle of small droplet trajectories. Proposed improvements to AGDISP MOD 4.0 (personal communication M. Teske) will incorporate a faster solution for small droplets, continuous deposition and a forest module. AGDISP MOD 4.0 was available for modelling runs of the ULV sprays at Dunphy.

(2) Weihs-Atlas Model

The major focus of this model is on the mean trajectory of droplets within the wing-tip vortices which are considered not to decay. The model includes evaporation but doesn't model spread due to turbulence so that deposit to the surface is calculated from the summing of mass when the trajectory intercepts the deposit plane. The model parameterizes a forest canopy as a series of regularly spaced hemispherical rows to which deposition is calculated. This model was not available for modelling the Dunphy scenario.

(3) FSCBG

FSCBG has recently been updated (V2) to link with AGDISP which provides the initial positions for the dispersion calculations of drops emitted from the atomizers. No indication is given as to when, during the vortex decay, the results are transferred from one model to the next. The model uses a slant Gaussian dispersion model in the calculation of surface deposition. Evaporation to a lower limit cutoff is calculated and the effective settling velocity adjusted accordingly. Dispersion and material translation are calculated using a single level "characteristic" wind speed and turbulence to describe the meteorology between the emission and deposition zones. The canopy impaction module is presently being modified and the original version (Grim and Barry, 1975) was not utilized in this study. Deposition to a surface (surface reflection = 0) can be calculated at prescribed heights and downwind locations from the spray line. FSCBG with the vortex and canopy modules omitted was used to model the Dunphy scenario.

(4) PKBW

The PKBW model is a linking of two models; the full VORTEX WAKE code (Teske, 1976) and a previously developed Lagrangian trajectory model (Picot et al., 1986). The flow field generated by the VORTEX WAKE code is used to calculate the trajectories of the droplets (assumed as a passive tracer encountering no drag or gravitational effects) which are trapped within the vortices. Inherent in the running of the VORTEX WAKE model is the decay of the vortices due to background turbulence, cross-wind shear or ground effects. The VORTEX WAKE model is run until the flow field of the vortex associated with an initiated droplet position decays into the background turbulence field. Within the PKBW model, dispersion is calculated by following individual droplets which are effected by instantaneous vertical fluctuations calculated, using a Markov chain technique, as they are advected downwind. Wind and turbulence profiles are parameterized for all stability classifications. The canopy module in this model has been tuned to the Dunphy site and is presented in terms of average foliage area per square metre of ground. Deposits to the canopy and ground are typically calculated to 400 metres downwind of the spray line. Selected Dunphy trials are modelled in Picot et al, 1987.

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*Micronair AU 4000 — MICRONAIR (AERIAL LTD.)

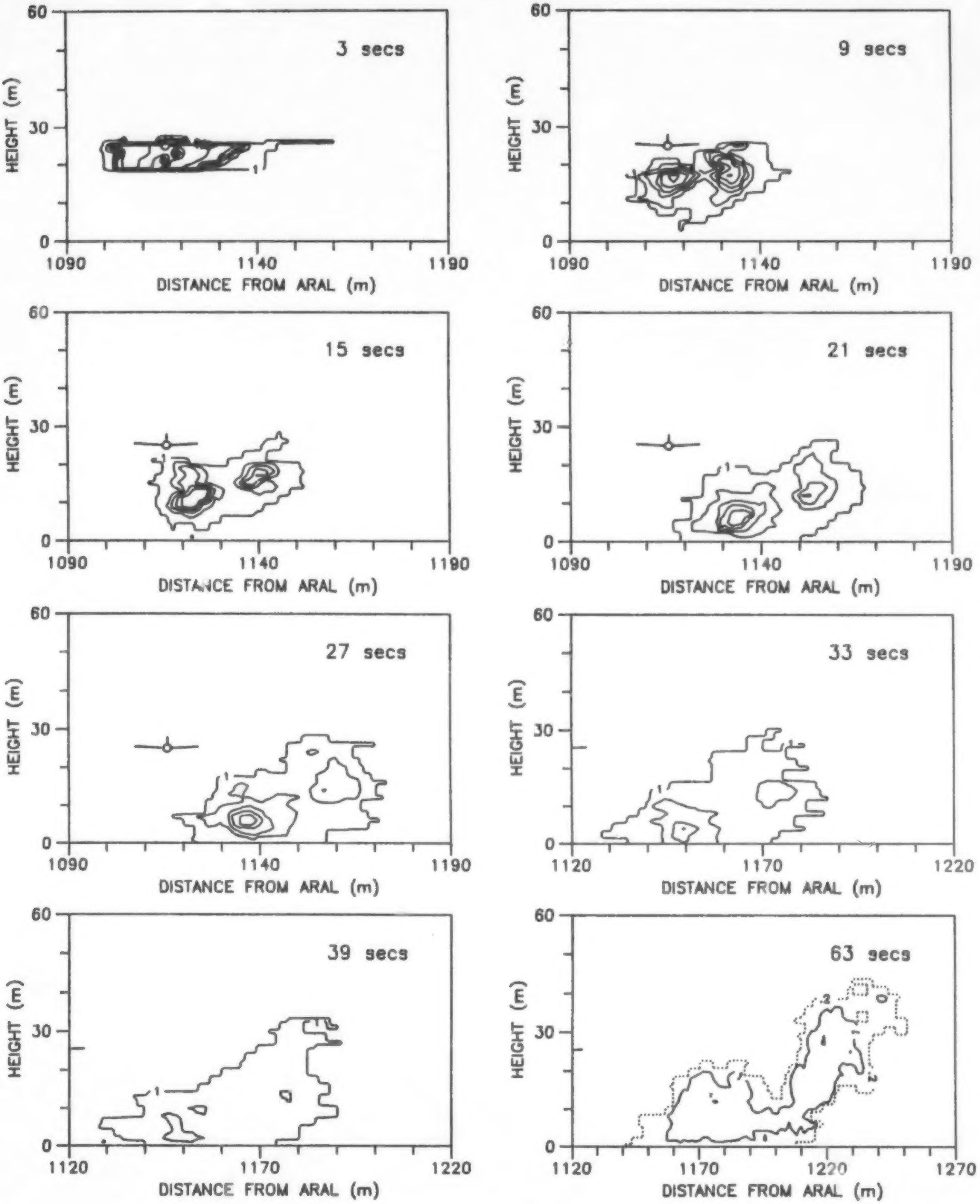

FIGURE 2: CROSS-SECTION MAPS FOR TBM SPRAYING OVER CLEAR-CUT

DROPLET TRAJECTORIES UNDER VORTEX CONTROL

Since the sink velocities of the wing tip vortices often exceed the average settling velocities of the droplets in ULV sprays, they can act as an efficient transport mechanism to move pesticide from the aircraft to the canopy. Using AGDISP, the influence on droplet trajectory due to droplet size (Figure 3) is modelled for a 20 second simulation of the TBM vortex. In this figure, the trajectories have been plotted with respect to the centre of the upwind vortex for a case of no vortex decay. Release height was 44.5 metres and the vortex centre dropped approximately 15 metres during the 20 second simulation. Only the upwind vortex is modelled with a crosswind of 1 m/s assumed at aircraft height. The drop range is characteristic of the class sizes for a ULV spray (Picot, et al, 1987) with the inboard and outboard nozzles characteristic of the two ends of the boom arms on a TBM. In particular it can be seen that the 180 micron droplet released at the inboard location tends to drop out of the vortex whereas the smaller droplets (60, 20 microns) remain trapped within the vortex. At the outboard location, the effect is not as pronounced although the large drops are tending to spin out of the vortex. The AGDISP model suggests that, even during the initial stages of the vortex descent, droplet segregation begins to occur so that the location of the droplet at which background turbulence takes effect will be droplet dependent given the same initialization position. It is also worth noting that for the sub-80 micron drops, the vortices play a dominant role in moving the material from the aircraft to the target.

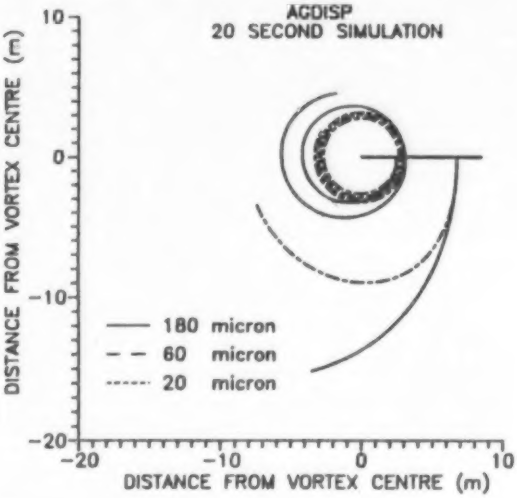

FIGURE 3: AGDISP DROPLET TRAJECTORY SIMULATION

PARAMETRIC STUDIES ON THE MODELS

Following the parametric study of Picot et al. (1986), an evaluation of the models for various operational parameters was conducted. In that study, Picot et al modelled the deposit up to 400 m downwind of the spray line for varying stabilities, wind speeds and effective release heights (the height at which the spray cloud dispersion is driven by background turbulence) using the emission spectrum for the 11010 Tjet. No vortex was included. The normalized wind speed profiles used for the neutral and unstable cases were considerably less than for the stable case for a given u* while above the canopy, the normalized vertical turbulence for the unstable case was greater than for the other two stabilities. Subsequently, the turbulence intensity (used as the standard deviation of elevation for FSCBG) was least for the stable case. The canopy used in that study was characteristic of the Dunphy site with the average vertical foliage density profile showing a maximum near 10 metres. The results of that parametric study for drift past 400 metres (Figure 4) are represented by the solid lines for various effective release heights as a function of the cross-wind speed at the emission height. The model predictions for drift suggest that the dominant factor influencing drift is the effective release height of the spray cloud with different stabilities playing a minor role as does wind speed at emission height. The individual points are the results of Picot et al (1987) for both the TBM with 11010 Tjets and the Agtruck with Micronairs. The results include the full WAKE code in PKBW. The aircraft type, stability and aircraft height identify each point. In comparing the model predictions for the two aircraft, the drift from the Agtruck is only marginally greater for all cases despite the stronger vortex associated with the TBM (2 times stronger than for the AgT) and the somewhat larger emission spectrum from the TBM (Picot et al, 1987). For the lightest crosswind case, the vortex lifetime is sufficient to move the spray cloud from a release height of 44 metres to an effective release height near 30-35 metres. For the higher winds, the increased background turbulence leads to a shorter vortex lifetime with a subsequent effective release height closer to the actual emission height. A further study on the effects of stability for an emission at 36 metres, now shows a substantially greater drift for the unstable case than for the stable case suggesting that the major influence of stability (or turbulence) is on vortex lifetime rather than on drift due to turbulent dispersion. The TBM U36 result highlights this where the drift for the unstable case is equivalent to the neutral run (TBM N44) for a TBM flying 8 metres higher in winds that are close to twice as great.

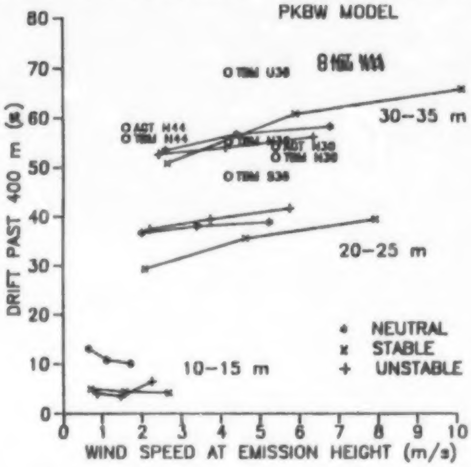

FIGURE 4: PARAMETRIC STUDY USING PKBW

Since the FSCBG model was run without the canopy submodule, a deposition surface at 10 metres, the height of maximum foliage density, was chosen as being representative of the total deposit to the canopy and floor. Using the canopy deposit results of Picot et al (1986) for the neutral case with effective release height of 10-15 metres, Figure 1 and Table 6 of that paper indicate that material entering the canopy will deposit very quickly (90% of all droplet sizes deposited within 20 metres). Also from the normalized wind profiles used in that study, the wind speeds are all approximately equivalent at 10 m for a given u*. However, there is a sacrifice in that total deposit is calculated so that foliage to ground deposit ratios cannot be investigated nor can droplet distributions throughout the canopy.

The results of a similar parametric study using FSCBG are presented in Figure 5 using essentially only the Gaussian dispersion model of Cramer et al. (1972) for the TBM 11010 Tjet spray with no vortex. The characteristic wind speed and standard deviation of elevation were chosen at the release height although previous runs using depth averaged values between release height and deposit height of 10 metres showed little difference. Only the 20-25 metre and 30-35 metre cases are modelled since without a canopy, the 10-15 metre in canopy release was not appropriate. As in Picot et al (1986), the effect of stability is not great. The significant difference between the two model predictions is in the stronger influence in FSCBG of release height wind speed on drift beyond 400 metres and the more minor contribution of the effective release height. However, the results of FSCBG are bounded by the parametric study of Picot et al. (1986).

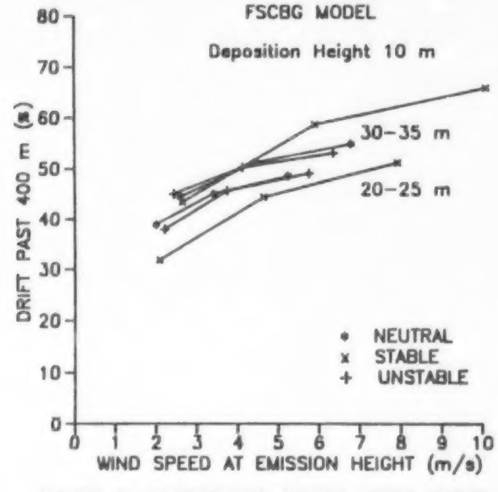

FIGURE 5: PARAMETRIC STUDY USING FSCBG

A further parametric study (Figure 6) was carried out on FSCBG to look at deposition patterns for varying droplet sizes as influenced by different operational parameters. For a light wind case with light turbulence (standard deviation of elevation = 0.6 degrees), the model predicts deposit distributions centred at increasingly further downwind distances with increasing spread and a tendency toward a skewed profile for the smaller drops. Results from AGDISP would be similar however without the skewed nature for the small drops. As the turbulence increases (characterizing conditions from stable through unstable) the peak in the deposit profile draws back closer to the spray line and the profile takes on a skewed nature. Deposition results from AGDISP would show the peak deposit at the same location for all cases but with increased spread due to turbulence. For the 100 micron droplet, the total deposit to 400 metres decreases substantially with increased turbulence while for the 60 micron drop, the deposit increases slightly due to the initial position of the deposit profile for the low turbulence case. For large variations in the elevation angle (ie. unstable case), there is little difference between the deposit profiles for the two droplet sizes.

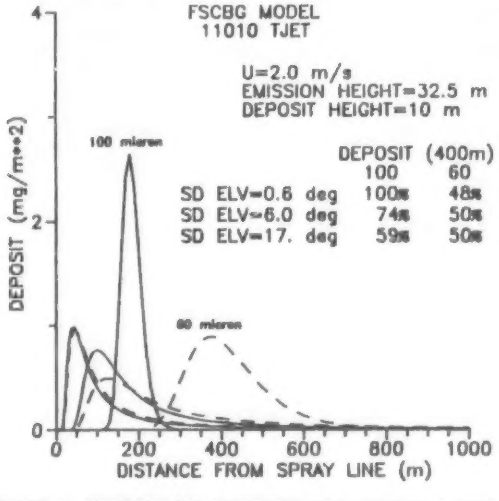

FIGURE 6: DEPOSITION PATTERN FOR VARIOUS DROP SIZES USING FSCBG

In Figure 7, the total deposit results of FSCBG for the emission spectrum of a 11010 Tjet are reviewed. Under highly turbulent situations, deposit due to the difference in emission height is not significant since the spread in the cloud more than compensates for the height difference. Emission height wind speed has a slight effect in decreasing deposit with increasing speed. However, as the turbulence is decreased, the effects of both emission height and wind speed are amplified so that under more stable situations, the model predicts a more significant difference due to emission height but with wind speed still dominating.

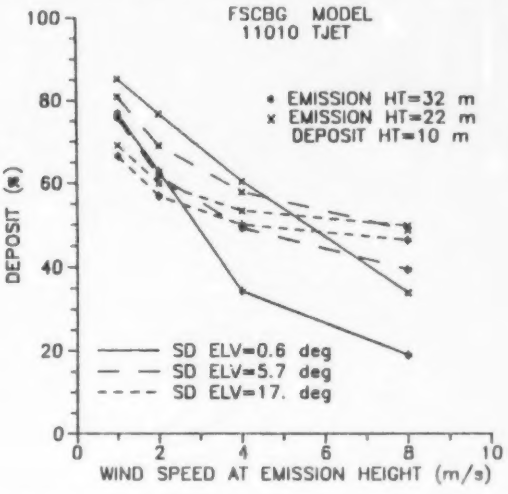

FIGURE 7: VARIATION OF TOTAL DEPOSIT DUE TO OPERATIONAL PARAMETERS USING FSCBG

COMPARISONS WITH DUNPHY 1984/1986 RESULTS

In 1981, the National Research Council began a series of co-ordinated experiments under the auspices of the New Brunswick Spray Efficacy Research Group to establish the effects of meteorology on off-target drift (Crabbe et al, 1982). These experiments culminated in two sets of experiments near Dunphy Airstrip in 1984 and 1986 to assess the effects of meteorology and operational parameters on deposit and drift. These trials utilizing two spray aircraft, a TBM with 11010 Tjet atomizers and an Agtruck with Micronairs, provided foliage and ground deposits to 1 kilometre and drift profiles to 300 metres above ground at selected downwind locations. All data presented here are with respect to the emitted non-volatiles assuming an emission rate of 1 gm/metre of flight line. For further details see Picot et al. (1987) Table 4.

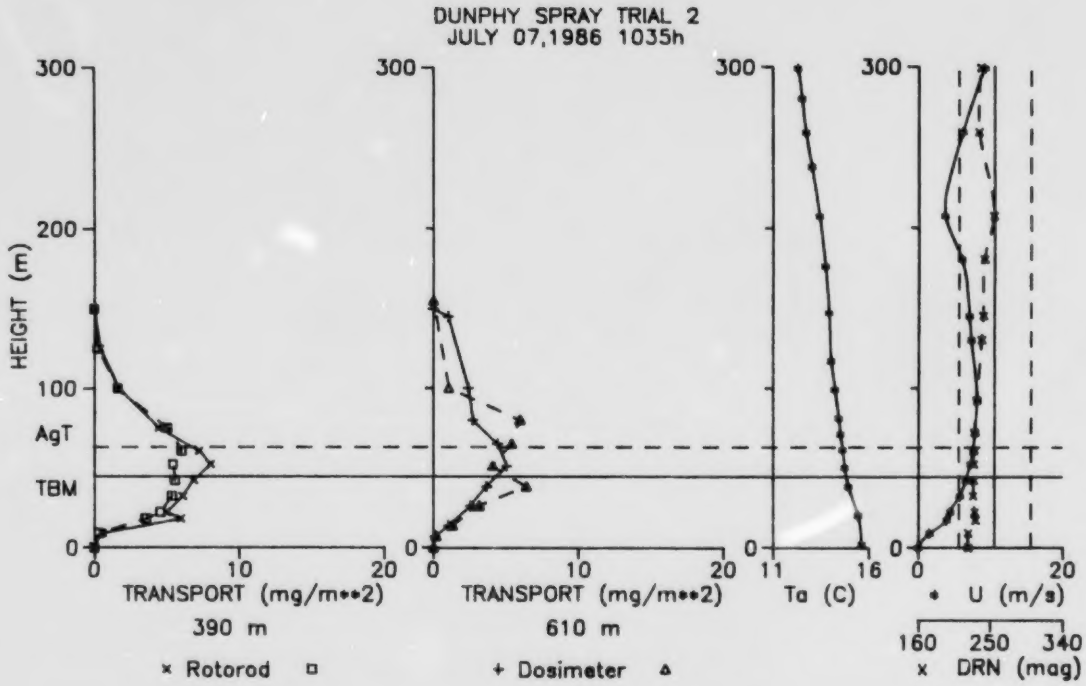

FIGURE 8A: DUNPHY TRIAL 2, 1986 — METEOROLOGY AND DRIFT

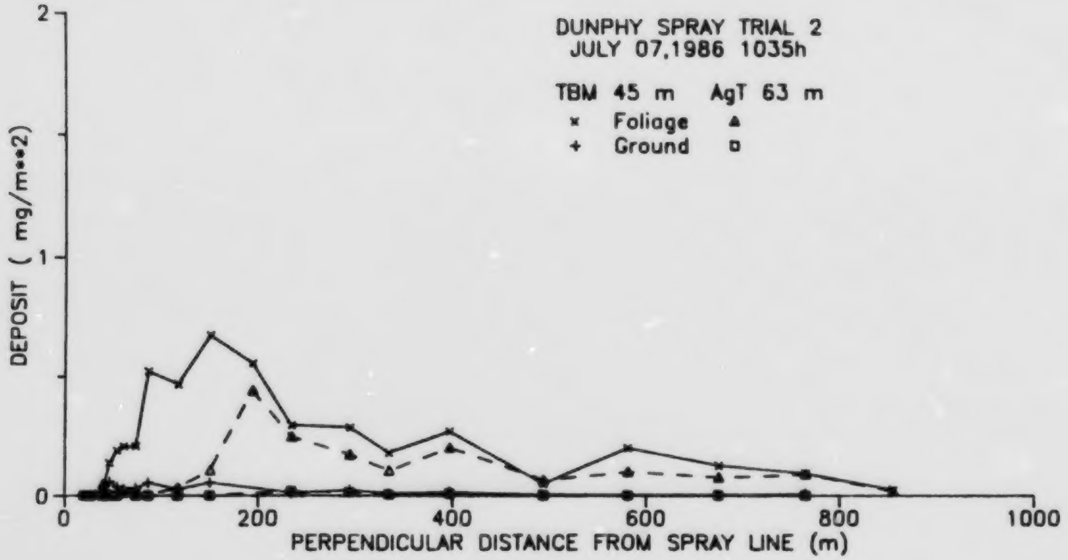

FIGURE 8B: DUNPHY TRIAL 2, 1986 — FOLIAGE AND GROUND DEPOSIT

Trial #2, 1986 (Figure 8a) took place during the mid-morning of July 07. Minisonde flights coupled with tower measurements indicated near neutral conditions to 300 metres. Cross-winds were brisk at 7.6 m/s at 60 metres with a subsequent much higher average flight line being taken by the Agtruck (63 metres) than by the TBM (44.5 metres). Wind direction was relatively constant from canopy top (17 metres) to emission height being an average 20° south of the perpendicular (255° magnetic) to the spray line. The drift data from rotorods on a 65 metre meteorological tower at 400 metre indicate a well dispersed cloud centred near the spray height drifting past the 390 metre downwind location. By 610 metres, the dosimeter measurements from a tethered balloon indicate that the cloud had grown somewhat vertically with the maximum still near the height of the spray line. The deposit data to 1 kilometre (Figure 8b) indicate a substantially greater foliage deposit from the TBM over the first 200 metres downwind from the spray line. Also the peak deposit for the TBM is closer to the spray line than for the Agtruck while beyond 400 metres the deposits are comparable. The ground deposit for both aircraft is a small fraction of the foliage deposit over the full downwind distance. In Figures 9 a, b, the measured total deposit (the sum of foliage plus ground deposit) is compared to the model predictions of AGDISP, FSCBG and PKBW. Due to the lack of canopy modules for AGDISP and FSCBG, the deposit for these models was calculated to a plane 10 metres above ground level. FSCBG did not incorporate aircraft wake while AGDISP modelled the TBM (24 Tjets) with vortex decay = 1. The results for PKBW (Picot et al, 1987) are the sum of the foliage plus ground deposit. The measured data (Figure 9a) give an integrated deposit of 16.5% of emitted non-volatiles with a material balance at 400 metres of 62.9%. PKBW underpredicts the measured deposit out to 100 metres and then overpredicts to 400 metres with a calculated total deposit of 29.6% of emitted non-volatiles. Beyond the peak deposit, the deposit drop off is consistent with measurement although the absolute deposit is too high. FSCBG matches the downwind position of the peak deposit but tends to over-predict deposit at all downwind distances. The integrated deposit to 400 metres is 35.7% of emitted non-volatiles. Beyond 400 metres, FSCBG compares well with measurement except for the anomaly at 700 metres which is felt to be due to reflection at the elevated inversion. AGDISP on the other hand tends to underpredict total deposit out to 150 metres and shows a rapid fall-off beyond 350 metres. The rapid decrease is due to two reasons, namely the Gaussian deposit formulation but probably more a consequence of the time limitation of the program runs. Indeed, runs for droplets less than 80 microns in diameter were never completed due to the extremely short integration step. The integrated deposit to 400 metres was 12.7% of the emitted non-volatiles, however only 54% of the mass of the emission spectrum was modelled. For the Agtruck (Figure 9b), only the FSCBG and PKBW models were run. Both models predict the shift of the maximum deposit away from the spray line due to increased aircraft height. Both models overpredict the measured deposit beyond 150 metres. Total deposit to 400 metres predicted by FSCBG and PKBW is 21.0% and 10.7% respectively compared to measurement of 8.9% with a material balance of 49.6%. The shape of the deposit drop-off is well matched by FSCBG. The fact that FSCBG without a vortex module matches the location of the peak deposit suggests that in this high cross-wind run the lifetime of the vortices was very short and therefore did not contribute significantly to the downward displacement of the spray cloud.

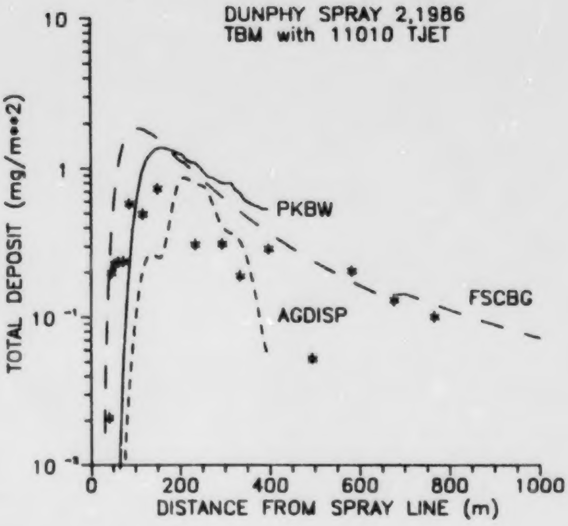

FIGURE 9A: MODEL PREDICTION OF TOTAL DEPOSIT FOR TBM

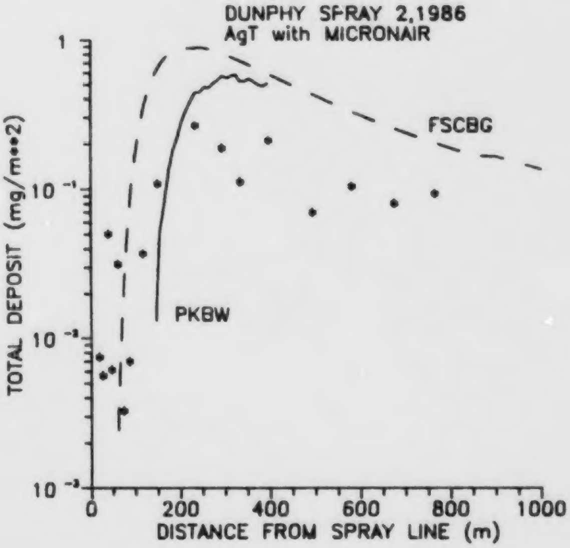

FIGURE 9B: MODEL PREDICTION OF TOTAL DEPOSIT FOR AGTRUCK

The second case study is for Trial 6 (Figure 10a), an early morning stable case of July 17. The flights were made within a surface based inversion to 130 metres with a weaker inversion at 200 metres. Through this layer, wind speed increased linearly from canopy top to 4.2 m/s at aircraft height. Both aircraft flew at the same height with average wind direction within 10 degrees of the perpendicular to the spray line. Drift measurements indicated a confined drift cloud centred at emission height with substantially more material airborne from the Agtruck than from the TBM. Comparisons with Trial 2 show peak transports that are 1.5 to 2.5 greater than for the July 07 study. By 910 metres, the drift clouds were very similar with extended vertical mixing having occurred. The deposit data (Figure 10b) show a very spikey deposit for both the TBM and Agtruck over the downwind distance to 1 kilometer. With very light winds within the canopy, a major fraction of the non-volatiles is deposited on the ground.

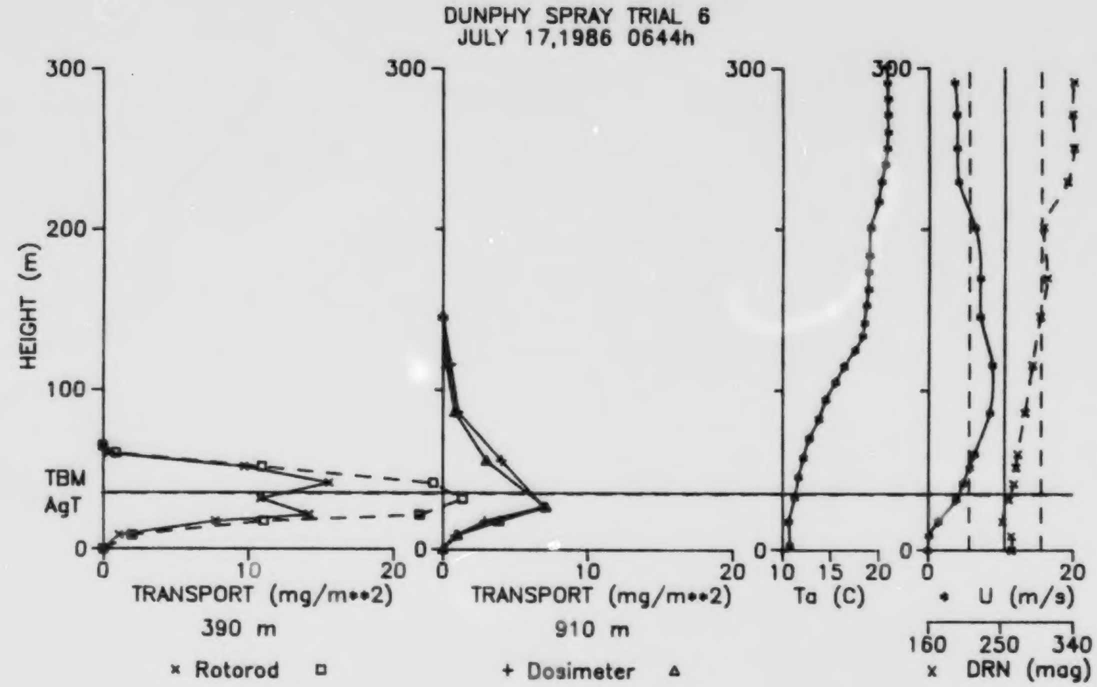

FIGURE 10A: DUNPHY TRIAL 6, 1986 — METEOROLOGY AND DRIFT

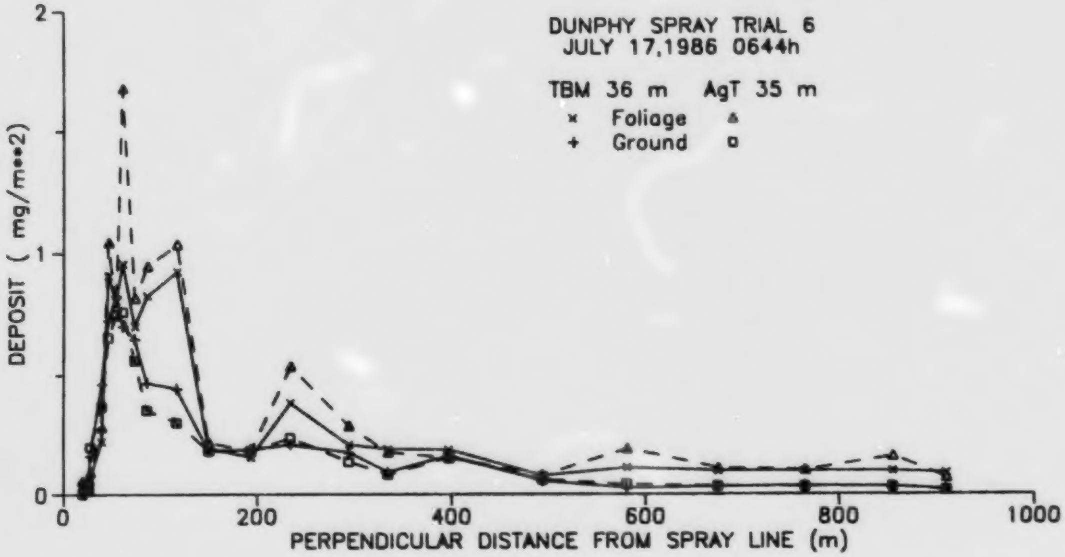

FIGURE 10B: DUNPHY TRIAL 6, 1986 — FOLIAGE AND GROUND DEPOSIT

Model predictions of total deposit are compared to measurement in Figures 11a, b. For the TBM, both PKBW and FSCBG predict the deposit peak further out than was measured suggesting that the vortex played a more important role than was modelled in moving material to the forest. Certainly this would explain the FSCBG results which had no vortex module. On the other hand, AGDISP predicts the peak deposit closer to the spray line than was measured based in part on the assumed weak decay factor. As before only droplet sizes greater than 60 microns were modelled. Both PKBW and FSCBG predict the deposit shape beyond the measured peak deposit while AGDISP decreases far too rapidly for reasons discussed previously. Total deposit to 400 metres compared to measurement of 26.8% with a mass balance of 77.5% is 51.7% for PKBW, 33.3% for FSCBG and 26.3% for AGDISP. For the Agtruck (Figure 11b) the FSCBG results are almost identical to those for the TBM suggesting that in this case the droplet spectrum difference between the two aircraft did not significantly effect the total deposit. PKBW results indicated a shift of peak deposit away from the spray line with an overall reduction in total deposit. Both models overpredicted the measured deposit beyond 100 metres as well as the total deposit to 400 metres (PKBW = 43.6%, FSCBG = 32.4%, MEASURED = 28.8% with material balance of 111%). Beyond 200 metres, the measured deposit decline is well matched by both models.

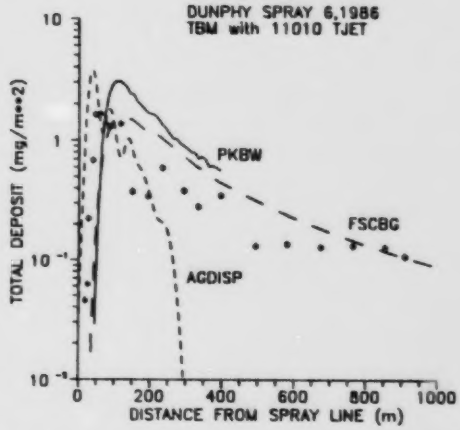

FIGURE 11A: MODEL PREDICTIONS OF TOTAL DEPOSIT FOR TRIAL 6 FOR TBM

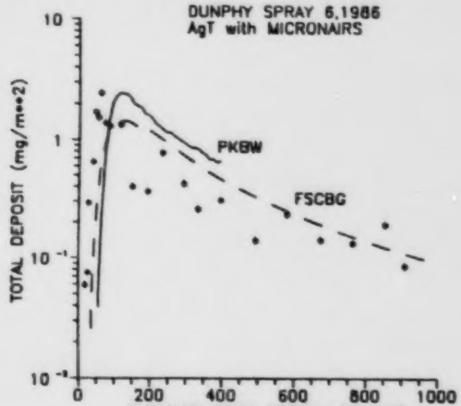

FIGURE 11B: MODEL PREDICTIONS OF TOTAL DEPOSIT FOR TRIAL 6 FOR AGTRUCK

The model comparison of total deposit to 400 metres with measured deposit is summarized in Figure 12 for the Dunphy 1986 data for both the TBM and Agtruck. In general, both FSCBG and PKBW overpredict total deposit compared to measurement. It must be recognized, however, that mass balance was not always achieved for the Dunphy experiment and hence the measured deposit data are subject to error. No estimate of this error has been given. The FSCBG deposit data tended to band between 30 and 50 percent for all case studies except for the two Agtruck cases, one flown at a high emission height, the other for moderate winds with low turbulence. PKBW for the 2/86 and 6/86 cases also overpredicts the total deposit, however the model tends to predict the greater observed variation in deposit for the four case studies. Only with the running of the remainder of the Dunphy cases using PKBW can a complete evaluation be done.

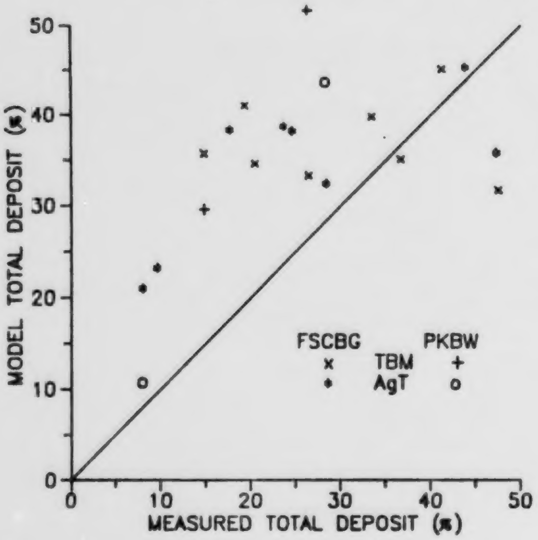

FIGURE 12: COMPARISON OF MEASUREMENT AND MODEL PREDICTIONS OF TOTAL DEPOSIT

CONCLUSIONS

Three of the four models have been evaluated against the ULV spray scenarios at Dunphy. The Atias-Weihs model was not included in the intercomparison due to the fact that total mass (non-volatile and volatile component) was modelled. Results (Weihs and Atias, 1987) suggest, that in all cases modelled, all of the non-volatiles were deposited within 400 metres with no drift. AGDISP in conjunction with FSCBG can strengthen FSCBG in terms of the WAKE VORTEX code. However, extensive increases in computing time may preclude its usefulness when applied to ULV spray scenarios. Based upon the Dunphy case studies, the Cramer dispersion model predicts the deposit shape beyond the maximum deposit; generally, however, the absolute deposit is high compared to measurement. Given the agreement in shape, this model should prove useful in evaluating the effects of operational spraying on off-target deposits. The PKBW model also effectively models the deposit shape to 400 metres but with an overprediction. An extension algorithm will have to be incorporated in order to calculate long range deposit and therefore be useful in a regulatory context. Also utilization of the VORTEX WAKE code flow field in the dispersion model may have to be readdressed for extended vortex lifetimes with larger drops. The major advantage of PKBW will be the capability of direct comparison of spray cloud movement and dispersion with spray mapping results. AGDISP presently suffers from significant computing time associated with sub-80 micron drops. By utilization of a different scheme for droplet motion, all droplet sizes could be modelled leading to a more complete model in terms of ULV sprays.

ACKNOWLEDGEMENTS

The major assistance of Dr. R. Hoff, F. Froude and J. Arnold, contributed to the completion of the ARAL mapping study in New Brunswick. The study was jointly funded by Atmospheric Environment Service and Forest Protection Limited. Finally, the efforts of M.A. Teeter in typing the manuscript are appreciated.

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SESSION V DISCUSSION PERIOD

Panel Chairman — R.S. Crabbe
Panel Members — J.W. Barry, A.J. Bilanin, C.R. Bowman,
J.J.C. Picot, D. Weihs, R.E. Mickle

(Editor's Note: For this session, the Panel Chairman has taken a different approach in documenting the Discussion Period from the tapes made during the Symposium. Because of the complexity of this particular Session, he has first taken some pains to describe the salient physics of each model presented in order to assist the reader of these proceedings in interpreting the background of some of the discussion. He then summarizes the discussion period as accurately as the tape audio quality permits rather than recording, verbatim, the questions and answers as other Panel Chairmen have attempted to do. As Panel Chairman, he has taken the liberty of inserting some of his own comments on situations addressed in the discussion period. I think this has been an appropriate departure from the norm for this particular suggestion and, in the summarized statements made, we hope that none of the discussion participants have been grossly misinterpreted.)

Session V brought together leading modelers whose studies of deposition and windborne droplet drift from aerial pesticide applications have appeared in the literature. Five invited papers describing four numerical models and the fifth comparing model results to a common data set were presented. The session began with the description by Jack Barry (USDA Forest Service) of Program Wind (Wind in Nonuniform Domains) and continued with the first of the two invited papers modeling deposition data from Program Wind, Bilanin et al (AGDISP) and Geary et al (FSCBG Version 2), presented by second-author Bowman. The chairman then introduced the Dunphy experiment and the next two speakers modeling the Dunphy drift cloud and deposition data, Picot et al (the PKBW model) and Weihs et al (the Atias Weihs model). Mickle closed the speakers' portion of the session with a paper comparing the numerical products of AGDISP, FSCBG and PKBW to the Dunphy deposit data. The session ended with a discussion period in which the panel, comprising five speakers and the chairman, answered questions from the audience.

The predictions of AGDISP, which computes mean droplet trajectories in the Lagrangian sense using vortex and propellor wake velocities, and trajectory variance about the mean using second order turbulence closure, were applied to a selection of ground deposition studies including that from Program Wind Phase 3 involving a Lockheed C-130 spray aircraft. AGDISP models the aircraft wake by fully rolled-up inviscid vortices with empiricized circulation decay, rather than by the vortex wake viscous code (VWVC) of Bilanin et al (1978) which includes viscous vortex rebound, on the grounds that most of the deposition occurs before rebound occurs. The author indicates that the factor-of-two and better agreement which was demonstrated would further improve with more complete documentation of field parameters.

Results from FSCBG 2, which is a sloped Gaussian plume model featuring the canopy penetration model of FSCBG and incorporating the AGDISP vortex code, were also applied to the forest/plantation scenario in Program Wind Phase 3. This was the first application of FSCBG 2 to spray deposition data and it generally achieved factor-of-two agreement despite the hazards of the Gaussian plume assumption. Like FSCBG, FSCBG 2 is menu driven. Both models include an evaporation module although the Phase 3 study used a non volatile spray formulation.

The prediction of the Dunphy field data by PKBW and Atias Weihs followed. The PKBW model, which has turbulence closure and vortex modules adapted from VWVC, is also a Lagrangian model but includes a novel canopy deposition model as well as a ground deposition model. PKBW achieved good agreement with the measured vertical droplet dosage (time-integrated) profile at 390 m from the flight line in the neutral (high wind) Dunphy spray and reproduced the measured longitudinal deposition profiles of 'active ingredient' (the 17% non volatile volume fraction) from this and another spray within a factor of two (the qualifying remarks applied to the AGDISP model/data comparisons apply here as well).

The Weihs Atias aerial forest spray model, which is adapted from their earlier model for open terrain, differs from the others by neglecting turbulent diffusion. A novel result of this model is the prediction of the effect of crosswind shear on the vortex sheet roll-up process which had not been analyzed previously. This model replaces trees by spanwise rows of semi circular cylinders to represent a rough surface and calculates the longitudinal droplet deposition profile onto a plane 14 m above ground (0.5 cumulative foliage fraction height) which the author suggests is probably too high for the 'effective canopy height' at Dunphy (the aerodynamic displacement length, 11 m at Dunphy, may be a better choice for a model which lacks a specific foliage deposition module). The model deposit predictions also include the unevaporated water so that only qualitative skill could be demonstrated in predicting the Dunphy data.

In the model evaluation paper, Mickle first presented some results of mapping a TBM spray cloud with fast lidar then compared predictions of AGDISP, FSCBG and PKBW (the Weihs paper was not available) to the Dunphy deposit profiles from both aircraft used in this study, a Grumman TBM and a Cessna Agtruck. FSCBG and PKBW generally overpredicted the measured deposition to 390 m but were superior to AGDISP, particularly FSCBG, in reproducing the tail of the deposition profile.

AGDISP appeared to demonstrate superior skill in predicting the onset of deposition but there is an uncertainty with its parameterization of vortex strength decay and it contains no foliage deposition code. On the other hand, Mickle also believes that until PKBW is applied to all ten Dunphy/86 trials, rather than just two, a complete evaluation of it is difficult.

Following the formal presentations, it was the audiences' turn and a number of interesting questions were directed to the panel. Not a few concerned the AES lidar spray cloud mapper. **Drummond** (NRCC) queried **Mickle** on the presence of only one region of high backscatter return (droplet concentration) in the TBM lidar data rather than two, one from each wingtip vortex. **Mickle** explained that it was an artifact of the presentation inasmuch as an earlier lidar study of a C-188 spray revealed two line clouds. **Green** (FPMI) inquired whether the lidar was a realistic tool for measuring wind drift and **Mickle** replied that its backscatter data contains no droplet size information so that its performance was relative but not yet quantitative, although, in principle, inserting a droplet size spectrum and an evaporation code into the lidar software could render it quantitative, but **Picot** cautioned that some account must be taken of the droplets that precipitate out early. **Raske** (CFS) remarked on the wide difference between lidar indication of drift (10%) and the model prediction (40-50%) and **Mickle** replied that in the lidar case, the wind speeds were much lighter. **Mineau** (CFS) inquired why AES couldn't use the evaporated ULV spectrum to render the lidar quantitative (evaporation usually proceeds rapidly for droplets in the ULV size range, i.e., smaller than about 100 mic dia) but **Mickle** said the emitted spectrum was required as well as the evaporation rates and **Picot** agreed. **Mickle** indicated a field experiment involving the lidar and cloud mass profile measurements is necessary to confirm this use of a 'modified' lidar.

Model/data comparison was also the subject of a number of queries. **Maybank** (SRC) asked **Picot** regarding PKBW's four fold modeling difference in ground deposit between the TBM and Agtruck when the foliar deposit was 'identical' and **Picot** stated that the difference was probably due to changes in atmospheric thermal stability, inversion conditions giving larger ground deposit than the neutral condition (it actually appears to be a function of wind speed in Table 7 of Picot et al). In response to an observation from **van Frankenhuyzen** (FPMI) that FSCBG outperformed the other models in predicting Dunphy deposit data although it contains no vortex wake to transfer material from spray release to canopy, **Mickle** stated that he believed his evaluation used high wind speed (high turbulence) cases where wake decay is relatively fast and therefore vortex effects minimal. **Akesson** (Univ of CA, Davis) observed that Mickle's model evaluation did not identify the drift hazard associated with inversion (stable) meteorological conditions, but **Mickle** said that the models showed that the 'effective droplet release height' moved up toward aircraft height with increasing turbulence as a result of shorter vortex lifetimes, thereby raising wind drift, and **Picot** agreed pointing out PKBW results showing higher deposit (lower wind drift) with reduced aircraft height. A result of this discussion was that PKBW's prediction of less wind drift in stable flow was considered to be a model function (the effective release height would tend to move up toward aircraft height due to the buoyant effect of the vertical density gradient on the vortex wake in a stable atmosphere). **Lo** (AES) observed that Weihs' model of vortex rebound lacks realism when using a wavy surface to approximate the forest inasmuch as the forest is a porous medium and **Weihs** agreed, but stated that the model agreed so well with the Dunphy data the first time that he decided not to make the necessary changes.

One reason for model/data disagreement may be the inevitable presence of experimental error in the field measurements. **Hoff** (AES) pointed out that **Payne** (FPMI) had alluded to less wind drift in higher wind speeds in his paper whereas model results (PKBW and Mickle) said otherwise. **Crabbe** explained that although the high wind speed (7 m/s) neutral Dunphy trial (#2) had shown less material in the drift cloud than the light wind speed (4 m/s) neutral trial (#4), there was a problem with material balance in Trial 2 which rendered the effect of wind speed uncertain.

Aerial application strategy was also discussed. **Ray** (FRI, NZ.) asked the panel what would be the effect on wind drift of using a short spray boom. **Weihs** stated that on a fixed wing aircraft, a boom longer than about 70% of the wingspan would lead to droplet entrainment in the tip vortex and therefore drift. A shorter boom would lower drift but at the expense of swath width and hence would increase the number of spray passes for a given area. **Bilanin** observed that increasing spray altitude broadens the swath width from a single nozzle but also increases the time interval for drift. To achieve the same swath width from low altitude requires a long boom which would again increase drift by feeding material into the tip vortex. **Picot** stated that higher near field deposition occurs with higher canopy wind speeds provided that the point of emission is near tree top, otherwise drift increases with wind speed and, as a matter of operational strategy, the pilots usually stopped flying in any case when they considered wind speeds (and turbulence) too high for safety. He further argued that the applicator's quest for increasing efficacy could be answered by using smaller droplets and an aircraft with strong downwash to deliver them into the canopy. **Picot** continued in response to a question from **Maass** (Scott Paper Co.) that this desirable aircraft characteristic is found in helicopters. **Akesson**, however, cautioned against emphasizing the helicopter as a spray vehicle because its high aerodynamic downwash is only achieved at a speed low enough to render it uneconomic. **Picot** observed that in the future high efficacy spraying would be more expensive in any case and continued, in response to **Freemark's** (CFS) query, that the Dunphy single spray line data applies to the multi swath incremental operational spray by the mathematical process of offsetting single swath results by the swath interval and summing. (**Bowman** said the Program Wind Phase 3 study included some multiple swath applications).

On the matter of information transfer, **Austin** (United Fruit Co.) asked regarding the panel's recommendations to the aerial forest sprayer as a result of Dunphy. **Picot** reemphasized the use of small droplets and high downwash aircraft and **Crabbe** stated that aerial applications in stable periods should be avoided since the ULV Dunphy spray data confirmed much larger wind drift in thermally stable (inversion) atmospheric conditions than in turbulent conditions because the wind speed at spray altitude was higher leading to higher drift, the canopy wind speed lower leading to lower droplet impaction efficiency on foliage and the turbulent transfer to bring droplets into the canopy flow from above was absent.

No further questions were forthcoming so the Chairman closed the modeling session.

AFTER-DINNER ADDRESS TO SYMPOSIUM

ADDRESS TO THE SYMPOSIUM ON THE AERIAL APPLICATION OF PESTICIDES IN FORESTRY

Dr. Larkin Kerwin

President, National Research Council of Canada

(Editor's Note: This is a reprinting of the notes used by Dr. Kerwin in his address to the Symposium attendees following the Symposium banquet, 21 October, 1987. It is reprinted with his kind permission.)

It is a pleasure to address this Symposium on the Aerial Application of Pesticides to Forestry. Admittedly, your subject is detailed and highly specialized. But beyond those details, I see in it a remarkable union of physics, aerodynamics, chemistry, plant biology, medicine, and economics.

This is indeed a rich blend — and it lies squarely within that cross-disciplinary tradition which has proven so fruitful in science. By connecting abstract research to concrete needs, you are in the enviable position of serving both the general cause of human knowledge, and the specific needs of human beings.

Your work represents a vital element in the maintenance of Canadian forestry — the single largest industry in this country. In that sense, your success or failure will have implications not just for your own work, but for the livelihoods of literally hundreds of thousands of our fellow citizens.

All of you in this room are well aware of how important forests are to Canada's economy. Regrettably, most Canadians are not. This is nothing short of astonishing given that Canadian forestry directly employs approximately 300,000 people. Indirectly, it affects the jobs and livelihood of another 700,000. That makes one million Canadians supported by trees!

Canada now annually produces around $30 billion worth of lumber and other wood products, pulp and paper, and forest derivatives. One out of every seven dollars that Canadians earn from manufacturing is derived from our forests.

Even more importantly, well over half of this production goes to export, making the forest industry the single largest contributor to Canada's positive but precarious trade balance.

There is a good deal more that could be said about the tremendous economic impact of forestry in Canada. Suffice it to say that it is a gigantic engine, driving other parts of Canada's private and public economy.

In many provinces, the forest products industry is the largest single purchaser of manufactured goods. And annually, it generates more than $1 billion in federal taxes, and a similar amount in provincial levies.

These raw statistics, however, only give a partial picture of what forestry means to Canada. There is also a human side to the story. That aspect concerns the hundreds of thousands of individuals whose livelihoods depend on forestry.

To take just one example, in Canada today, there are at least 300 communities where forestry is not only the largest industry — it is the only industry. Were that industry to falter, to decline, or to disappear, those communities would quickly become ghost-towns.

It is unsettling, therefore, to realize that this is precisely what may very well happen. The possibility that Canada's forest industries will disappear is stronger now than at any point in the industry's three hundred year history.

There is a threat to Canadian forestry. It is real. It is imminent. It is dangerous. The fact is that because of mismanagement, intense foreign competition, and inadequate research, this tremendous generator of jobs and wealth may eventually become only a dim and distant memory.

The symptoms of decline in Canadian forestry are everywhere. For example, I wonder how many Canadians realize that almost half the telephone poles used in eastern Canada, and half of the railway ties used by CPR are imported!

That we have to import timber into a country as richly forested as our own is a sad reflection of the deepening malaise confronting Canadian forestry.

There are still some who do not see the crisis. After all, our forest products industries have recently returned to prosperity after a sharp period of recession in the early 1980s.

Yet much of this transient prosperity stems from a falling Canadian dollar which makes our exports cheaper — at least in the short term.

In the long term, however, fluctuating exchange rates are a weak foundation upon which to base our most important domestic industry. Indeed the world in which our foresters are attempting to survive is far more competitive than we thought possible.

For example, the forestry industry's traditional mainstay, bulk commodity exports, are increasingly threatened from two directions — by competition from new timber producers, and by substitute materials used in building and packaging.

International competition has intensified because technological progress in silviculture has led to new processes that make use of a much wider range of wood species and wood qualities.

Moreover, other countries are opening up new regions of forest to exploitation. Many of them have become self-supporting, and some have even started exporting on their own account. As a result, Canada's share of the world market for forest products is under attack.

The intensification of international competition comes at a time when demand for wood products is weakening. Some traditional markets are not growing as quickly as they used to — and some are declining.

Wood products are being challenged by a wide range of new materials based on aluminum, concrete, plastic, ceramics, and steel. These materials are emerging as substitutes for many of the items derived from forestry — especially in building and packaging, two areas of traditional forest product strength.

Canadian forestry is being challenged — by new competitors, by weakening global demand, and by alternative materials. What is worse, we may no longer be in a strong position to meet that challenge.

The brutal reality is that we have less and less to meet it with. To take one stark example, Canada's share of total world softwood exports is approximately 44 percent. Yet we only have 14 percent of the world's remaining supply of still growing softwood.

Our market share of softwood exports cannot last if we run out of softwood to export. And unless we awaken to the crisis, we will run out.

The demands we place on our forests are considerable. For example, every day's issue of the Globe and Mail consumes the equivalent of 2,000 trees.

Multiply that by all our other daily papers, by the reams of paper used in our offices, by endless computer printouts, by wrapping papers and parcels, by millions of letters and circulars, and by a multitude of boxes, and you get some idea of daily demand for pulp and paper alone.

Yet even this tremendous demand could easily be satisfied from Canada's forests if we managed them properly. But we do not.

Franklin Delano Roosevelt once commented on the different approaches of Europe and North America to forestry: "They treat timber as a crop. We treat timber resources as if they were a mine".

With fewer forests to spare, the Europeans have managed, tended and harvested them as carefully as they do their farms. In Canada we have been profligate, confronted by a seemingly endless forest, we have strip-mined it thoughtlessly and now seem surprised to discover that it may be running out.

Every year, Canada's forested area is reduced by some 2 million acres — an area larger than Prince Edward Island. What is worse, a third of the forest area we lose each year is rendered permanently unproductive by inadequate restocking.

Yet there is more confronting Canadian forestry than just poor forest management. Canada's forest products industry is also in danger of losing the scientific and technical edge that once made it a world leader.

Let us take the pulp and paper industry as an example. Two or three decades ago Canada was the recognized leader in pulp bleaching and paper making. However, this country failed to sustain that lead by committing adequate investment capital, human resources, and research.

By the beginning of the 1980's, Canadians were spending about one-third of one percent of their pulp and paper sales on research and development. This was only a third of the proportion being spent by our chief competitors.

And our competitors' research did not just go into new products, it also developed new production processes. The Canadian pulp and paper sector is well behind its competitors in overall levels of automation — using computer integrated manufacturing systems to improve overall productivity as well as provide flexibility in meeting market demand.

As a result, Canada's pulp and paper industry has been overtaken by others — most notably by the Swedes and the Finns, and increasingly by the Japanese. To match Swedish R&D levels, for example, we would literally have to more than double the number of people we currently employ in pulp and paper research.

The end of Canadian leadership in pulp and paper is only one example of our failure to keep up. The fact is that in-house R&D levels throughout the Canadian forest industry trail behind comparable efforts in the United States, Sweden, and Finland.

To take another example, the average commitment to R&D on solid wood in Canada is about .3 percent of sales — again about a third of what our chief competitors spend.

Our shortcomings in R&D go beyond our failure to maintain a competitive edge in new products and processes. Canadians have also failed to design and manufacture world-class machinery and equipment to support the forestry industry.

As a result, Finland, West Germany, Sweden and the United States are the dominant sources of machinery and equipment for the forest products industry.

Despite these somber results, there are still those who argue that Canadians do not need to do more forestry research. That we can survive if only we become "fast-followers" capable of quickly absorbing the technologies of others.

In fact, the past decade has shown that this strategy will permanently keep us behind our competitors. No matter how eager we are to adopt the work of others, there will always be costs and delays involved in transferring foreign technology here.

What is worse, as technology from abroad becomes more complex, and without a developed capability of our own, we may find it increasingly difficult to adapt foreign technology. We will simply lack sufficient numbers of people who understand it well enough to apply it.

There is no question but that forestry R&D in Canada is seriously underfunded. Canada spends less than .007 percent of its gross domestic product on R&D in forestry. Indeed, a single U.S. forest products company spends more on R&D than the entire budget of the Canadian Forestry Service.

Against this gloomy backdrop, there are a few encouraging signs. A recent federal-provincial forestry development agreement injected an additional $125 million for forest management and R&D in 1986–87. Though encouraging, however, this is at best only a symbolic start.

The Science Council estimates that at least $20 billion in new investment will be needed over the next five years just to maintain the present relative position for Canadian forestry.

Even if the Canadian forest industry were to commit that imposing sum of money, it would not solve all of its problems. Canadian forestry needs more than money. It needs a strategy for research and innovation.

Three elements of that strategy stand out in particular:

- we need to provide lower cost and higher quality wood feedstocks,
- we need to improve the products we derive from our forests, and the processes by which we derive them, and
- in order to achieve the first two objectives, we need to increase our R&D efforts in forestry.

The first objective of Canada's forestry strategy should be the provision of lower cost and higher quality feedstocks. Here the watchwords are cost and quality. We don't just need more trees. We need better quality trees, easily harvestable trees, and trees with specifically desirable characteristics.

That means paying closer attention to restocking. It means better forest management. And it means using the latest that biotechnology has to offer.

We cannot afford the laissez-faire attitudes of the past. In the sixteenth century, when humanity knew a lot less about rational resource management, the French philosopher Michel de Montaigne could encourage his readers to "Let nature have her way. She understands her business better than we do".

Since then, we have learned that nature is not strong enough by herself to recover from the increasing demands we now place on her. And letting her have her way is merely a euphemism for laziness on our part.

We are now in a position to help nature along. For example, genetic engineering is capable of producing new "supertrees" which grow rapidly and are more disease and pest resistant. And I certainly needn't tell this audience about the implications of biotechnology for pest control — for example in the use of *Bacillus thuringiensis* against spruce budworm.

The second element of a Canadian forestry strategy should be to improve the products we derive from our forests and the processes by which we derive them.

The forests already contribute to a surprising range of goods — paint, soap, plastics, rayon, explosives, cleaning fluids, photography film, shatterproof glass, coil conditioners, hospital gowns, and food.

In the future, new kinds of pulps, specialty papers, and lignin-based chemicals will be developed, and automobiles may even be powered by fuels derived from forests.

In all of these areas, we have to think carefully about what markets want, how best to satisfy them, and how to ensure that the greatest part of the value added to forest-derived products stays with Canadians.

The answer to these questions lies with the third element of a national forestry strategy — research and development. Peter Drucker has said that "the only means of conservation is innovation".

In today's economy every industry has to use high-tech if it is to survive. The fact that forestry is resource-based does not in any way reduce its need for advanced technology.

I have already suggested that countries such as Sweden have secured a position of leadership for themselves in forestry because of their intensive R&D efforts. We can do no less if we don't want to fall further behind, and we will have to do a lot more if we want to catch up.

Canadian private companies will have to devote more resources to R&D. They have no choice. They should take advantage of relatively favourable current conditions to increase their R&D efforts and their technological capabilities. They cannot afford to wait until it's too late.

Further, since the forest industry cannot afford the costs of duplicating every R&D effort, we must become better in this country at conducting cooperative research through organizations jointly funded by industry and government.

We already have three such bodies — The Forest Engineering Research Institute of Canada, Forintek Canada Corporation, and The Pulp and Paper Research Institute of Canada or Paprican. They can act as the focal points for a greatly expanded program of forestry R&D in the future.

We should also remember the contributions that can be made to Canadian forestry by institutions such as the National Research Council.

For many years, the NRC has worked with forestry companies, and with other R&D bodies such as Paprican.

The NRC's divisions have worked and are working on areas as diverse as plant genetics, pest control, aerial spraying, enzymatic degradation, waste treatment, utilization of spent sulphite liquors, fiber analysis, the use of membranes for chemical separation, sensor development, forest fire research, and even the effects of chain saw vibrations on workers.

The list could go on. Suffice it to say, however, that the NRC is capable of making major contributions to the future of Canadian forestry.

The key is to pull these diverse strands together — to foster greater effort and greater cooperation among corporations, research institutions, universities, and governments.

This conference provides an excellent example of how different disciplines can be pulled together in a highly complex way to yield concrete benefits to industry and to the country.

In the same way, but on a much grander scale, Canadian forestry will have to assemble different disciplines, diverse institutions, and disparate resources, for the great task of saving this country's single largest industry.

Canada's position in forestry recalls Aldous Huxley's comment on humanity's profligate use of its resources. "Such prosperity as we have known is the consequence of rapidly spending the planet's irreplaceable capital."

But the forest is replaceable — if only we use our intelligence and devote our attention to it. Canadians have a choice. If we choose correctly, and manage our forests well, they need not run out. Their beauty and their riches will continue to be available to serve us and future generations in perpetuity.

You are one of the spearheads of this correct choice and of this wise management.

Bon courage.

SESSION VI

OPERATIONAL CONSIDERATIONS

SPECIFICATION OF MOST ACCEPTABLE SPRAY WEATHER

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ABSTRACT — The data derived from several years of field trials in New Brunswick and Ontario are examined to ascertain the spray weather conditions most conducive to promoting spray efficacy while minimizing drift. The data suggest that these objectives may not necessarily be complementary. On the premise that confinement of the spray material to distances within the setback limits (1-2 km) is the priority, the effect of atmospheric turbulence and windspeed on cloud behaviour is discussed; within this context, the influence of (fixed-wing) aircraft type and flying height is also considered. From a complex matrix of data, admittedly lacking completeness, trends are discernible and a thumbnail set of guidelines is offered for operational consideration.

The most acceptable spray weather tends to prevail in a turbulent atmosphere, provided the height of the mixing layer is limited. Very acceptable spray weather can also occur in thermally stable and neutral conditions. Windspeed is less important in the unstable situation, but becomes influential as stability increases. Probably the least acceptable spray weather from the viewpoint of both drift and efficacy obtains in the complete absence of turbulence, such as may occur at sunrise following clear skies overnight; the caveat to the very stable case, however, is that the condition may allow the spray aircraft to fly sufficiently low, terrain permitting, for the downwash to induce droplet impaction.

RÉSUMÉ — L'analyse des données relevées sur le terrain durant plusieurs années au Nouveau Brunswick et en Ontario est étudiée pour assurer les meilleurs conditions d'épandage: réaliser une efficacité maximale de dépôt et minimiser l'influence de la porté éolienne. Les données suggèrent que ces objectifs ne vont pas nécessairement de pair. Les effets de la turbulence atmosphérique et de la vitesse du vent sur le mouvement du nuage d'épandage sont présentés; et ceci en supposant que la distance tampon applicable à la pulvérisation de pesticides est limitée à 1-2 km. Les effets de la hauteur de vol de l'appareil et du type d'appareil sont aussi étudiés.

Une étude approfondie des données (incomplètes) permet de relever les conditions favorables d'épandage et d'offrir certaines directives opérationnelles. L'épandage est favorable dans les cas suivants: conditions atmosphériques thermiques stables, stratification neutre et spécialement les conditions instables caractérisées par des profondeurs de brassage limitées. La vitesse du vent est un facteur moins important dans les conditions instables, mais a un effet marquant au fur et à mesure que les conditions atmosphériques se stabilisent. Les conditions les moins favorables sont en l'absence de turbulence: au lever du soleil et à la suite d'une nuit claire. Cependant, dans ces conditions, l'appareil peut voler à très basse altitude causant une turbulence; ceci favoriserait la fixation des gouttelettes sur les surfaces collectrices.

INTRODUCTION

The use of the descriptor 'most acceptable' in the above title carries with it the suggestion of the existence of a definitive answer to the weather factor in spray operations. Assuming for the moment this to be the case, that everything about the weather and how it affects spraying is known, attempting to specify these conditions may be unavoidably tinged with some arbitrariness, since what could be construed as 'most acceptable' to the operations manager may be less than ideal to the spray pilot or to the general public. The subject matter, then, allows for some poetic licence. For this reason but, more importantly, because we do not in fact have the weather factor completely in hand, a certain amount of interpretive subjectivity will be exercised in this paper when examining the experimental data which provides the basis of the Conclusions.

The data base examined here stems from an ambitious series of field trials carried out over a span of eight years, mainly in New Brunswick at the Dunphy test site. The experiments were designed, in part, to study the influence of a range of prevailing meteorological conditions on the atmospheric transport and dispersion of liquid chemicals aerially released over a forested area. A prime objective of the work was the elucidation of the role of atmospheric turbulence on windborne drift away from the target area; another was to determine the aircraft flight parameters and other factors which promote spray efficacy in the near field. In this regard, the term efficacy as used here pertains only to the physics of the aerosol transport and impaction processes without regard to the other, key elements of biology and entomology required in a complete study of spray efficacy.

The present paper, then, is an attempt to assess the results of the Dunphy drift and deposit experiments with a view to determining the weather conditions which enhance deposition — and, presumably, efficacy — while minimizing off-target drift.

BACKGROUND

The Dunphy project represents a collaborative effort between a number of independent research organizations, each contributing its expertise to a particular aspect. Thus, a team from the University of New Brunswick's engineering faculty (UNB) was responsible for measuring spray deposit, while a group from the National Research Council's Unsteady Aerodynamics Laboratory (UAL) undertook the airborne drift measurements. Using quite different approaches and techniques, the results obtained by the two groups when combined are impressive; in the last series of Dunphy trials (1986), for example, spray accountancy was often better than 80% over the near field sampling range, 0-400 m.

There is, however, an apparent inconsistency which arises with respect to interpretation of the data and the relative importance of the various parameters involved. In brief, the UNB school of thought holds that deposit within the first 400 m and, by inference, airborne drift are governed predominantly (if not entirely) by the altitude of the spray aircraft as well as, to a lesser extent, aircraft type. UAL, on the other hand, has concluded that drift at setback distances of 1-2 km is very strongly dependent on atmospheric stability, and so too is spray deposit.

How, then, to decide on the relevance of the prevailing meteorology and what constitutes the most acceptable spray weather? In the subsequent sections of this report the Dunphy trials will be reviewed and the data re-examined in the light of new evidence obtained from recent field experiments conducted by UAL near Kapuskasing, Ontario.

Measurement of Drift

UAL determines the airborne mass of spray drift by means of compact, chemical sampling devices mounted on meteorological towers or suspended from tethered blimps. The vertical dosage profile so determined, when combined with the measured windspeed profile, allows calculation of the total flux (g/m^2) of the drifting cloud across a plane some distance from the spray line. In practice two such determinations of the flux are carried out, one at 400 m, the other at 1-2 km downwind. Knowing the line source strength (g of active ingredient a.i./m of spray line), it is possible to compute the differences between the amount released and the total airborne fluxes at 400 m and 1 km and thereby arrive at the amounts deposited to 400 m and to 1 km, respectively. The mass budget equation, based on the safest of assumptions that Deposit + Drift = Quantity Released, takes the form (Crabbe et al, 1982)

$$\text{deposit to } x = q - \int_0^h U(z)D(x,z)\cos\theta(z)dz$$

where q is the line source strength, θ is the angle between wind direction and distance x measured normal to the spray line, h is the height of the cloud top and U is the mean wind speed at height z; D is

$$\text{dosage} = \frac{\text{mass of a.i. collected by sampler}}{\text{sampler collection rate}}$$

usually expressed in units of ng-min/L. Normalizing the budget equation to q allows calculation of % Drift and % Deposit.

The chemical samplers used by UAL in most of the New Brunswick experiments were narrow adsorption tubes through which the metered air sample was aspirated. This technique was suitable for the initial long-range drift study where only fine spray droplets were involved and for the breathing height dosage determinations where both droplet and vapour forms of the pesticide were to be collected. However, in subsequent studies involving the near-field measurement of larger, non-volatile tracer droplets problems of anisokinesis become apparent, and the samplers often underestimated the atmospheric content of the tracer, requiring very large corrections.

An improved version of the adsorption tube sampler, or dosimeter, was designed, gimballed and equipped with tail fins to track the vertical and lateral turbulence fluctuations and face into the wind; the device is pictured in Figure 1. Comparison with Rotorod samplers under the laminar flow conditions of a wind-tunnel gave excellent agreement, Figure 2, but comparison under turbulence encountered in the field still required as much as 50% correction.

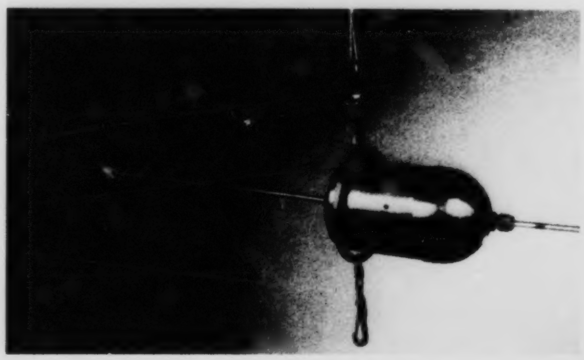

FIGURE 1: GIMBAL-MOUNTED AIR SAMPLER

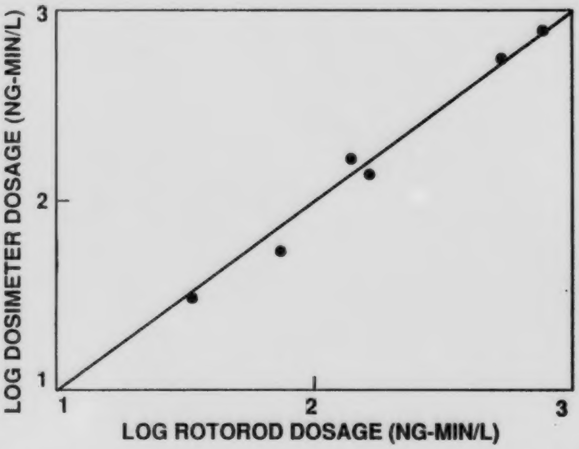

FIGURE 2: WIND TUNNEL COMPARISON OF ROTOROD AND AIR SAMPLER IN ULV DROPLET PLUME

For the most recent UAL drift measurements, at Kapuskasing, a lightweight Rotorod package (Fig. 3) was developed, five of which could be readily accommodated on a tethered blimp. UAL considers that the Rotorod device, when used with a non-volatile tracer such as tris (2-ethylhexyl) phosphate (TEHP) and in conformance with the manufacturer's specifications, provides the most economical and reliable sampler for windborne aerosols, in agreement with the findings of May et al (1976).

FIGURE 3: LIGHTWEIGHT ROTOROD/BATTERY PACK

Measurement of Deposit

Simply stated, the main objective in spray efficacy is to deposit uniformly as much as possible of the a.i. at the prescribed application rate onto the target foliage. The degree to which this objective is met may appear at first to be best determined through chemical analysis of the foliage. The direct measurement of foliar deposit, however, entails a difficult sampling protocol and time-consuming laboratory procedure requiring macerating the foliage, solvent extraction, one or more cleanup steps and solvent evaporation, prior to gas chromatographic analysis. The procedure is far too involved to be practical in a forest tract. For this reason UNB has developed a foliage simulator in the form of a V-shaped comb which can be readily washed with solvent to remove deposit. Made of aluminum, the device has undergone extensive calibration in the windtunnel and in the field to correlate the deposit collected with it to that collected on actual foliage from spruce, pine and fir. While earlier correlations exhibited excessive scatter (Riley, 1985), follow-up work has improved the reproducibility to an acceptable level (van Vliet, 1987).

In the most extensive series of field trials at Dunphy (1986), UNB deployed over 350 such foliage simulators at 3 sub-canopy heights at about 60 sampling sites in the 0-1 km downwind fetch, in addition to a complement of ground plate collectors. On the basis of a detailed tree survey in the area of type, size and density, the total spruce and pine foliage area was estimated, which, together with the correlated simulator deposits and ground plate measurements, allowed UNB to calculate the total foliar and ground deposition. A typical foliage deposit profile is reproduced in Figure 4 (taken from van Vliet, loc. cit.; TPP refers to a second tracer, tri-phenyl phosphate).

Determination of Meteorological Conditions

A prominent feature of the Dunphy project was the UAL 46-m meteorological tower (extended to 62 m in 1986) instrumented with an array of vector vanes and thermistor probes to measure mean wind speed, direction and turbulence intensities. The tower data was augmented by means of UNB's minisonde which profiled the wind and temperature fields to well above the topmost drift sampler, as well as by means of the AES tethersonde in 1986. The mean wind speed as a function of height was required to compute the airborne flux, as outlined earlier, and the temperature data enabled calculation of the heat flux for stability classification of the atmosphere.

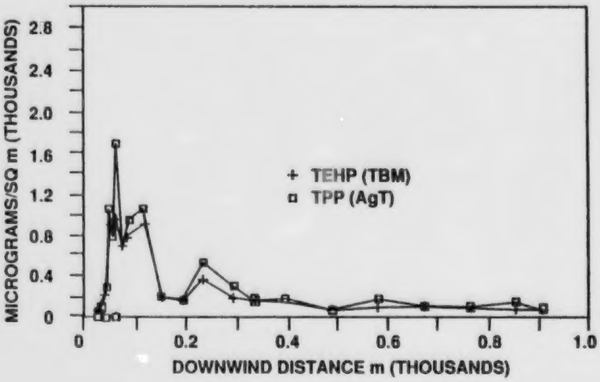

FIGURE 4: TPP AND TEHP DEPOSITS ON CANOPY

Atmospheric stability was the salient parameter of interest to the UAL drift study. Elsewhere in these Proceedings Professor R.B.B. Dickison provides a more thorough and expert account of stability classification than can be offered here; in lay terms, however, the following definitions will hopefully suffice:

(i) a *stable* atmosphere is defined as one in which the ambient temperature increases with height, and winds may be light to moderate; there is little or no tendency for the warmer air aloft to mix with the denser air near the ground;

(ii) an *unstable* or turbulent atmosphere is characterized by vertical air movement; the condition is often brought about by solar heating of the ground under clear skies an hour or two after sunrise, producing a negative temperature gradient (or lapse), or may be generated by strong wind shears over rough terrain; an unstable situation may be 'capped' with an inversion at some height, marked by the onset of a positive temperature gradient and a stable atmosphere above that level;

(iii) a *neutral* condition prevails when the temperature gradient is about -1° over the first 100 m above ground; the rarefaction of the atmosphere with height offsets any increase in density due to cooling; like the stable case, winds may be light to moderate, but in contrast to the stable case the neutral atmosphere is non-buoyant; hence, the descent of the aircraft vortices formed at spray height may be unabated until they intercept the forest.

Within the categories of Stable and Unstable, the adjectives, 'very', 'moderately' and 'slightly' denote gradations, while the term 'nearly' often describes the Neutral state. The approximate temperature change over the first 100 m above ground level associated with these gradations is shown in Table 1.

Likewise, a simplified classification of windspeed at spraying height is adopted here, according to the scheme presented in Table 2.

RESULTS AND DISCUSSION

The New Brunswick field experiments were conducted during the spring/early summer seasons of 1979 through 1984, and lastly in 1986. The final experiment, designed logistically to be the most comprehensive of the entire Dunphy exercise, yielded by far the most extensive and reliable deposit data; but, in keeping with the vagarious nature of the object under study, the weather, an unexpected squall occurred at the outset of the experiment which destroyed one of the two tethered blimp stations and badly compromised the drift portion of the study. For this reason the author has chosen, in the analysis that follows, to focus on the 1986 deposit measurements and the preceding 1979-84 drift results to discern the trends in spray cloud behaviour as a function of weather conditions.

New Brunswick Field Trials 1979-84

Long range windborne drift was the subject of the initial aerial spray investigation carried out by UAL and UNB at the request of Forest Protection Limited of New Brunswick (cf. Crabbe et al (1980)). A fuel oil formulation in which insecticide was replaced with the inert simulant TEHP was sprayed by a Grumman TBM in multiple (24-30) passes along a single line at the upwind end of a forest test range in the northern area of the province. A grid of 26 air sampling stations in three sampling arcs downwind at 7.5, 24 and 45 km measured tree-top concentrations of the drifting cloud; a few measurements were also made of the vertical concentration field with balloon-suspended dosimeters. The results clearly indicated a systematic trend in peak tree-top concentration with stability, the value at 7.5 km, for example, varying from about 5 ng/L in the stable case to about 1.5 ng/L in the neutral case, or 0.4 to 0.14 parts per billion, respectively. The lower concentration for the neutral case, attributed in part to enhanced deposition as well as to turbulent spread of the cloud, corresponded to about 6% airborne drift, compared to 16% for the stable case. These drift figures were computed by fitting the data points of the balloon dosimeters to a log-gaussian curve. The 6% figure agreed well with the 4.5% predicted in Crabbe and Reid (1980) for a comparable fenitrothion spray. Tree-top dosages vs distance are shown plotted in Figure 5.

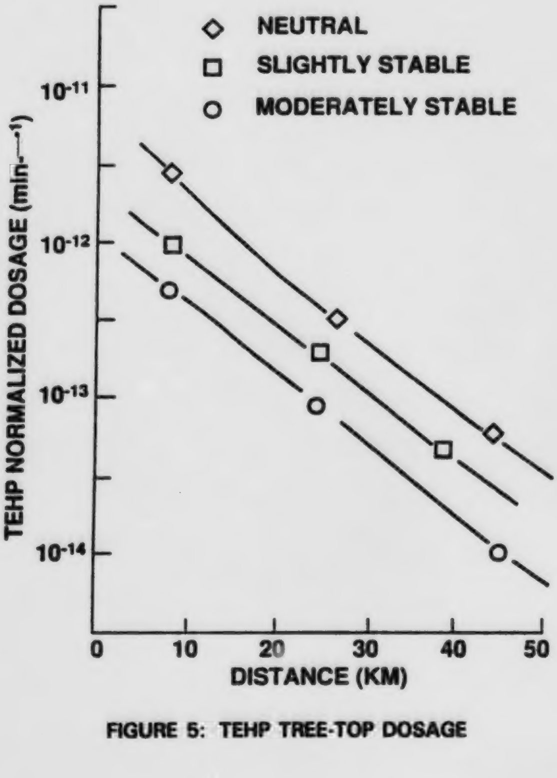

FIGURE 5: TEHP TREE-TOP DOSAGE

Concern over near-field exposure to operational spray clouds prompted the next experiment (Crabbe et al (1981)), designed ostensibly to determine breathing-height fenitrothion dosages from the spray line to 700-800 m downwind, for two cases: (a) TBM spraying of a uniform forest, and (b) AgTruck (AgT) spraying of an isolated woodlot having a clearcut downwind fetch. The result of interest to the present discussion which emerged from this experiment was the distribution of droplet sizes observed in the drifting cloud at 500 m, illustrated in Figure 6. It is noteworthy that most of the airborne mass collected with cascade impactors under the breezy conditions prevailing in these trials was associated with 4 μm droplets in the case of the TBM and 6 μm droplets for the slower flying AgT. That such droplets, which have negligible settling rates (~3 cm/min), were predominant at the sampling height of 1.5 m would seem to underline the influence of turbulence in transporting the cloud to well within the forest; at the same time, the lack of droplets in the 20-100 μm range at this level is probably indicative of their efficient removal through foliage impaction higher up.

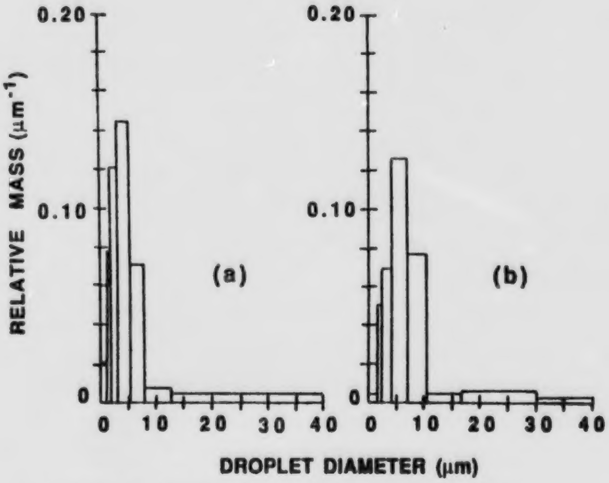

FIGURE 6: DISTRIBUTION OF DROPLET SIZES IN SPRAY DRIFT CLOUD 500 M DOWNWIND OF
(a) TBM SPRAY,
(b) AgT SPRAY

Both the long-range and near-field experiments had demonstrated an atmospheric aerosol content judged to be acceptable by the governing regulatory departments. In 1981, with the formation of the New Brunswick Spray Efficacy Research Group (SERG), research activity on spray cloud behaviour became focused more toward the efficient enhancement of spray deposition on the target foliage. UNB and UAL, for example, apart from conducting drift-deposit studies, investigated various spray nozzle designs best suited to produce droplets in the desired size range of 20-50 μm, the range considered to provide optimum foliar deposit in the New Brunswick scenario.

To provide a venue for the required spray efficacy field trials, a permanent test site was established in a forest area in central New Brunswick nearby the Dunphy air strip. Measuring roughly 10 km × 10 km, the tract was of moderate-to-low stand density, the coniferous portion comprised largely of spruce and pine (in the proportion of 3:1) having an average tree height of around 10 m and maximum tree height nearly double that. The UAL 46-m high meteorological tower was erected on a concrete base 400 m distant from the designated spray line for each year's activities at the site, and dismantled afterwards.

The ensuing Dunphy field trials from 1981 to 1984 saw refinements to the UAL air sampling techniques while UNB in conjunction with the N.B. Research and Productivity Council investigated new deposit measuring methods. Despite shortcomings of the adsorber tube dosimeter to provide quantitative data, it was nevertheless possible to distinguish trends, and in 1982 UAL concluded that ULV spraying should be conducted in conditions of atmospheric turbulence to minimize windborne drift, based on fenitrothion budget trials where the fraction of airborne mass of the drifting cloud at 400 m decreased in the order of

Stable > Neutral > Unstable

Both fenitrothion and aminocarb dosages were measured at mid-canopy and breathing height levels as well in 1982, and provided useful information regarding the risk of personnel exposure to drift: sub-canopy and breathing height concentrations were as much as 3 times lower in conditions of turbulence and slightly higher winds than in stable conditions, presumably owing to more efficient foliar scavenging of the spray droplets.

Attempts to redress the yawing motion of the blimp air samplers were only partially successful in 1983 with the addition of vertical fins to the devices. Five trials making use of the modified dosimeters were conducted to measure the drift of an aqueous TEHP-based emulsion. In the very stable case, considerably greater mass was airborne at 1200 m than was airborne in either neutral, slightly stable or slightly unstable situations, as anticipated. Among the other four trials, however, slightly lower drift was measured under conditions of neutral stability than under unstable conditions, a finding at variance with previous conclusions.

Uncertainty in the sampling efficiency of the dosimeter prompted the development of the gimbal mounting feature and bivane tail assembly for three-dimensional response of the sampler to atmospheric turbulence. This upgraded model was used in the 1984 spray efficacy trials at Dunphy. The response of the sampler was judged to be adequate for low frequency directional fluctuations, as at the 1200 m station where a rigid-tail blimp was deployed, but not at 400 m where the blimp used underwent rapid plunging motions. The results of the drift measurements at 1200 m are summarized in Table 3. The lowest drift fractions were observed to occur in unstable conditions with low inversion bases, Trials 3 and 5, the higher turbulence intensities in Trial 5 being especially effective in transferring the spray droplets into the forest. Considerably more drift was experienced in higher wind situations under neutral or stable stratification, Trials 1 and 4.

UNB deployed some 180 foliage simulators in the 1984 trials; about twice that number was used in the Dunphy 1986 experiment by which time earlier calibration problems had been circumvented.

Dunphy Field Trials 1986

In these trials two different spray aircraft were used, a TBM and a Cessna AgTruck. The TBM spray formulation was spiked with TEHP while the AgT mixture contained TPP as tracer. Each aircraft alternately sprayed the same line 5-6 times, thereby ensuring that identical meteorological conditions held, and enabling a comparison to be made of the influence of vortex strength on efficacy.

The UNB total deposit data (Kristmanson, 1986) from the nine documented trials conducted at Dunphy in 1986 are presented in Table 4. As alluded earlier, the Dunphy forest tract was non-homogeneous, being interspersed with patches of open areas; at the same time, the wind direction observed during the experiment varied by as much as 76° between different trials. These two factors in combination could affect the near-field deposit, as was subsequently observed in the (analogous) Kapuskasing situation. It may be more appropriate, therefore, in assessing spray efficacy to compare trials of similar wind direction, as has been done in Table 4. The Off-Axis Wind Angle$\Delta\theta$ shown in the table represents the deviation in wind direction from an imaginary line orthogonal to the spray line; fortuitously, the results lend themselves to even grouping along three wind axes. The following points of interest regarding weather effects are noted:

a) in Group A, conditions of neutral and moderate stability with light winds, Trials 4 and 6, yielded greater foliar deposit than did the uncapped, turbulent condition of Trial 7;

b) in the B grouping, the neutral and moderately stable states are again associated with high deposits; the effect of windspeed under stable conditions is also apparent, the light winds in Trial 3 effecting less deposition than the very light winds of Trial 8;

c) the comparatively low deposits obtained in Group C are likely the result of an unfavourable wind direction, in addition to the high wind speed/high flying height in Trial 2 and the uncapped, unstable condition of Trial 10.

An apparent trend of decreasing deposit with increasing aircraft height above ground is observed in the case of the AgT, noticeably exemplified by Trial 2. However, apart from this exceptional high-height/high-wind case, a similar trend is not seen with the TBM. When the Dunphy 1986 deposit results from Trials 3-10 are arranged into 'high', 'medium' and 'low' rankings, as in Table 5, a similar variation in deposit is observed for the TBM as is observed for the AgT, even though the spray height of the TBM was constant to within a few meters of 36 m. The argument that flying height is less critical for the TBM because of its stronger downwash is not a valid one to explain these results, since a uniformly high deposit would be expected for all trials around 36 m if that were the case.

The low aircraft height achieved with the AgT under the non-turbulent, low windspeed conditions of Trials 5 and 8 very likely contributed to the resultant high deposits, through aircraft-induced turbulence. On the other hand, the low deposits measured in Trials 9 and 10 when the TBM also flew low attest to the often predominating influence of the local prevailing meteorology. Moreover, aircraft spray height is not usually a negotiable operating parameter; the operational guideline of flying 100 ft (30 m) above the trees — which, for the Dunphy forest translates into a spray height of 45 m above ground level — is designed for both pilot safety and to minimize 'striping'.

The importance of atmospheric conditions relative to the flight parameters is also underlined by the Dunphy deposit data in another way. The overall average flying height for the TBM and for the AgT in Trials 3-9 was the same, 36 m. In spite of the TBM having a vortex descent rate some 50% greater than that of the lighter AgT, the overall average deposit measured from 0-400 m in these trials was 31% for the TBM and 29% for the AgT, a difference of less than 10%.

Kapuskasing Field Trials

The incompleteness of the drift data obtained from the Dunphy 1986 study prompted UAL to undertake a field experiment at a test site near Kapuskasing, made available through the courtesy of the Canadian Forestry Service, Sault Ste-Marie; the spray pilot and AgT aircraft were also provided by that department.

Two studies have been conducted to date at Kapuskasing, which will be described more fully in forthcoming reports from this Laboratory. In the preliminary study, the blimp-supported dosimeters were replaced with the compact, omnidirectional Rotorod devices (cf. Fig. 3), while in the follow-up experiment aerosol passive samplers were added to assess the spray deposition pattern and supplement the drift measurements. The passive samplers were 2.5 cm × 12.5 cm cylindrical forms of 16-mesh wire screen; having strands of 0.25 mm diameter, these samplers were designed for the efficient collection of ULV droplets down to the very low end of the size range. A photograph of the passive 'cage' sampler appears in Figure 7.

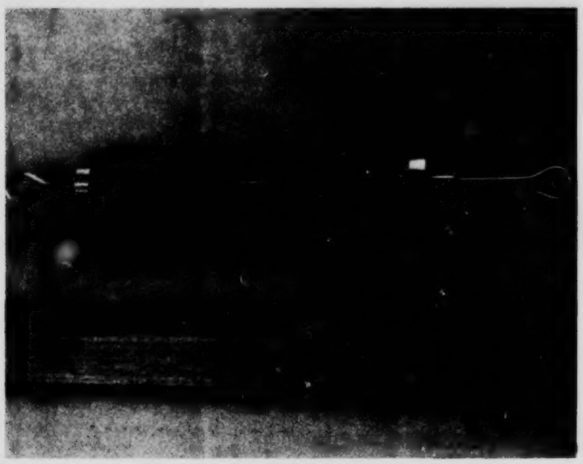

FIGURE 7: DROPLET PASSIVE SAMPLER

Three stability classes were investigated in the initial experiment. The normalized airborne dosages measured at 400 m and 1200 m for the three classes are shown in Figure 8, from which the trend is plainly seen that the windborne fraction of spray remained aloft longer in stable conditions than under the capped turbulent conditions. The vertical dosage profiles at 1200 m are plotted in Figure 9, which, when combined with the vertical mean wind profile, corresponded to airborne drift fractions of about 8% and 20% for the unstable and stable cases, respectively.

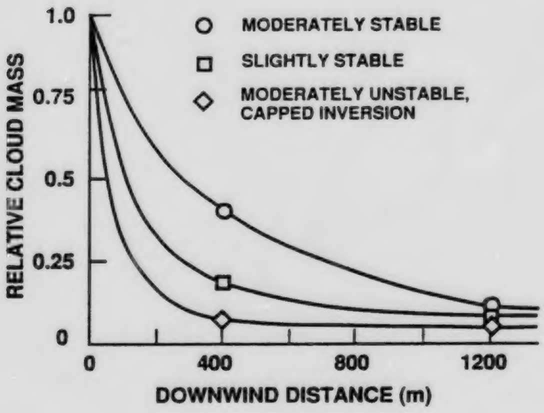

FIGURE 8: CLOUD MASS vs DISTANCE, KAPUSKASING TRIALS

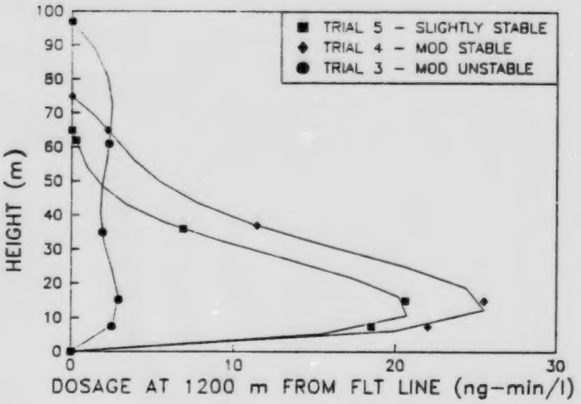

FIGURE 9: VERTICAL DOSAGE PROFILE AT 2200 m

In the second, more extensive Kapuskasing experiment, a total of ten trials were performed encompassing both drift and deposit measurements, the latter intended to provide a relative measure of total deposit as a function of weather conditions. The results of this work are summarized in Table 6. Since three different spray lines were used, depending on wind direction, the results are again grouped accordingly, to allow more appropriate comparison.

The entries in the column in Table 6 headed 'Cage Sampler Deposit to 400 m' are in arbitrary units of mass × distance, computed by integrating the area under the deposit vs distance distribution curve, an example of which is presented in Figure 10. The deposits were those collected on thirty cage samplers deployed at 1.5 m and 0.75 m heights above ground in the 0-400 m downwind fetch.

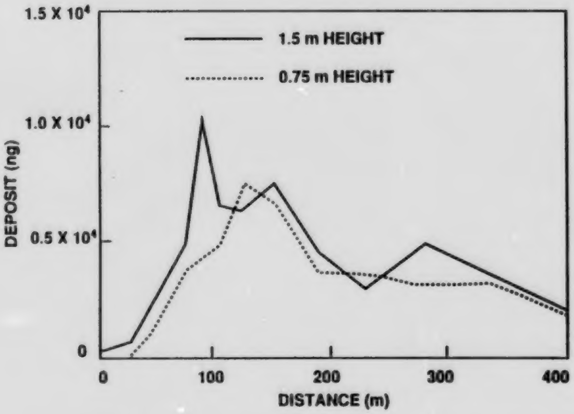

FIGURE 10: SAMPLER DEPOSIT MEASUREMENTS, KAPUSKASING TRIAL NO. 7

A wider range of atmospheric conditions was encountered in the Kapuskasing field trials which augment those of Dunphy 1986, and allow the following observations:

a) the lowest fractional far-field drift occurred under conditions of thermal instability limited by an inversion base, Trials 3, 7 and 11; a turbulent atmosphere not limited in height by inversion is associated with higher drift, Trials 1 and 10;

b) in conformance with the Dunphy deposit data, a moderately stable condition and very light winds (Trial 8) favour deposition and low drift, while stable stratification and moderate winds (Trial 4) enhance drift;

c) the very stable atmosphere of Trial 5 produced massive drift and little deposit.

Interestingly, in comparing the near-field drift and deposit figures of trials of similar wind direction, an anomalous trend emerges: both deposit and drift appear to be concomitantly lower under less stable conditions; cases in point are Trials 7 vs 10, Trials 4 vs 11, and Trials 2 vs 6. Similar instances (not detailed here) are also evident in the Dunphy data, where high drift/high deposit, low drift/low deposit may go hand in hand. While such behaviour could be coincidental and the result of experimental error, a plausible explanation presents itself.

Both the UNB comb sampler and the UAL cage sampler were designed to mimic such foliage as spruce needles, the target vegetation. The forest, however, is comprised of many more elements than these small-surface droplet receptors. It is suggested that as canopy winds and turbulence increase, broad leaf vegetation and other large-surface area elements become more efficient scavengers of the spray, thereby competing with the pine needles (or their simulator) and reducing the observed deposit. Thus, although Deposit as measured by the simulators may be down in the less stable cases when % Drift is also down, the total spray deposition in the forest as a whole can in fact be higher, as depicted by the lower airborne fraction. Some experimental evidence in support of this explanation is found in the results of a few comparison tests made at Kapuskasing between broad-leaf simulators (courtesy of N. Payne, Canadian Forestry Service) and the UAL cage samplers. The results, shown in Table 7, indicate that the leaf sampler collected about 70% more aerosol relative to the cage sampler in unstable as compared to stable conditions.

CONCLUSIONS AND SUGGESTIONS

The most acceptable spray weather from the point of view of minimizing windborne drift beyond 1 km is characterized by moderate instability and a capping inversion with a base height not exceeding ~400 m.

Very acceptable spray conditions can occur in neutral and in slight to moderate stability situations, provided winds are no more than moderate (< 6 m/s) in the neutral case, no more than light (< 4 m/s) in slightly stable conditions, and very light (< 2 m/s) in moderately stable conditions.

Extremes in either turbulence or stability constitute less acceptable spray weather, eg. an unstable mixing layer of unlimited depth, or, worse still, a thermally stratified atmosphere in which the temperature gradient exceeds 4 °C in the first 100 m above ground.

Airborne drift measurements can yield information on total deposit in the target area, but not necessarily on spray efficacy as defined by deposit on the target foliage; similarly, deposit measurements of the target foliage may not always reflect the true airborne drift fraction.

Table 8 is presented as a weather rating chart based on trends in far-field drift gleaned from several years of field experiments; it may require additional stability and wind categories for complete specification of acceptable spray weather, it undoubtedly could benefit by more precise information regarding when and for how long acceptable spray 'windows' are available. In conjunction with such information, the suggestion is offered here for spray operators to seek the development of a compact, economical microprocessor-based temperature lapse sensor to be mounted on spotter aircraft for a rapid assessment of atmospheric stability; such a technological aid could go a long way in alleviating public concern about drift.

ACKNOWLEDGEMENTS

The author is grateful to R. Crabbe and M. McCooeye for providing the Kapuskasing data and for many helpful discussions; thanks, also, to C. Dionne and S. Dodds.

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TABLE 1: Stability Categorization

Category	Temperature Change/100 m (°C)
Very Unstable	<-2
Moderately Unstable	-2
Slightly Unstable	-1.5
Neutral	-1
Slightly Stable	1
Moderately Stable	3
Very Stable	>4

TABLE 3: Percent Drift, Dunphy 1984

Trial No.	Stability Class	Windspeed m/s	% Drift at 1200 m
1	neutral	5.6 (moderate)	22.5
2	slightly stable	3.6 (light)	19.4
3	slightly unstable, inversion base 70 m	3.3 (light)	14.6
4	slightly stable	6.4 (brisk)	27.1
5	moderately unstable, inversion base 150 m	3.5 (light)	6.4

TABLE 2: Categorization of Winds

Category	Windspeed
Very Light	<2.5 m/s
Light	2.5-4 m/s (5.5-9 mi/hr)
Moderate	4-6 m/s (9-14 mi/hr)
Brisk	>6 m/s

TABLE 4: Percent Deposit to 400 m, Dunphy 1986

	Trial No.	Off-Axis Wind Angle$\Delta\theta$	Stability Class	Windspeed, m/s	TBM/AgT Height, m	% Deposit
Group A	4	13°	nearly neutral	3.5/3.5	36/37	33/24
	6	10°	moderately stable	4.2/4.1	36/35	26/29
	7	10°	slightly unstable, inversion base > 1 km	4.3/4.3	38/42	19/18
Group B	3	38°	moderately stable	3.5/3.0	40/35	37/25
	5	33°	nearly neutral	3.0/2.9	35/32	42/44
	8	41°	moderately stable	1.7/1.4	37/32	47/47
Group C	2	-26°	neutral	6.6/7.6	45/63	15/8
	9	-35°	moderately unstable, inversion base > 1 km	3.0/3.2	33/42	14/13
	10	-23°	slightly stable	3.7/4.4	35/42	20/10

TABLE 5: Effect of Aircraft Height on Deposit, Dunphy 1986

Relative Deposit	Trial No.	Average Deposit/Aircraft Height AgT	TBM
high	5,8	45%/32 m	45%/36 m
medium	3,4,6	26%/36 m	32%/37 m
low	7,9,10	14%/42 m	18%/35 m

TABLE 6: Drift and Deposit Measurements, Kapuskasing Trials

	Trial No.	Wind Direction	Stability Class	Windspeed m/s	Cage Sampler Deposit to 400 m	% Drift at 400 m	% Drift at 2200 m
Spray Line I (307°)	1	350°	moderately unstable, inversion base >1 km	2.6	51	>40	>30
	7	292°	slightly unstable, inversion base 200 m	2.9	53	39	29
	8	310°	moderately stable	1.9	61	54	32
	10	290°	moderately unstable, inversion base >1 km	4.2	57	52	>30
Spray Line II (262°)	3	282°	moderately unstable, inversion base 400 m	3.3	66	41	23
	4	250°	slightly stable	5.1	48	>80	46
	11	247°	slightly unstable, inversion base 300 m	3.8	31	51	20
Spray Line III (217°)	2	230°	moderately stable	3.0	86	87	50
	5	196°	very stable	3.2	12	>80	n.d.
	6	185°	slightly stable	4.4	70	45	n.d.

TABLE 7: Comparison of Cage and Leaf Sampler Deposits

Trial No.	Stability Class	Sampler Deposit, μg Leaf	Sampler Deposit, μg Cage	Deposit Ratio (Leaf/Cage)
1	moderately unstable	12.2	16.6	.74
4	slightly stable	2.4	6.4	.38
6	slightly stable	3.0	10.5	.29
7	slightly unstable	5.8	12.3	.47
10	moderately unstable	4.8	9.5	.51

Average deposit ratio { unstable cases – .57
stable cases – .34

TABLE 8: Acceptability of Spray Weather as a Function of Stability and Winds

Weather Conditions Stability	Weather Conditions Winds	Most Likely Time Period for Occurrence	Frequency of Occurrence	Acceptability Rating
unstable, inversion base >500 m	light to brisk	10 am to 5 pm	high	low
unstable, inversion base <400 m	light	2-4 hr after sunrise	medium	high
neutral(1)	light to moderate	2-3 hr after sunrise	low to medium	high
slightly stable	light	final 3 hr before sunset	medium	high to medium
moderately stable(2)	very light to light	final 3 hr before sunset	medium	high to medium
moderately stable(2)	light to moderate	final 3 hr before sunset	medium	medium to low
very stable	light	0-2 hr after sunrise	high	lowest

(1) Ideal neutral conditions occur mainly under cloud cover when ground heating and formation of thermals is suppressed.

(2) Drift and deposit under moderately stable conditions are strongly dependent on wind speed and flight parameters, ie. very low wind speeds (<2-3 m/s) and stronger downwash enhance deposition, higher wind speeds (>4 m/s) enhance drift.

THE MEASUREMENT OF SITE-SPECIFIC WEATHER FOR AERIAL PESTICIDE APPLICATIONS

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ABSTRACT — Documentation of on-site weather is important for aerial pesticide applications if maximum efficacy is to be attained and if thorough post-spray assessment is to be undertaken. This paper describes the use of a mobile minisonde system to obtain low-level soundings in support of aerial spray applications. During 1981-1987, a total of 526 minisonde soundings were conducted in order to provide meteorological documentation for experimental spray trials and for operational spruce budworm spraying in New Brunswick. More than half of these soundings were conducted in the vicinity of Dunphy airstrip, and many of these data could be compared with those from an elaborate tower-mounted system operated by the National Research Council. The comparisons suggest that adequate representation of atmospheric stability is possible with minisondes, differing by no more than one Pasquill-Gifford class in 90% of the cases. Furthermore, minisondes enable mixing depths to be determined more satisfactorily than by other means.

RÉSUMÉ — La documentation des conditions météorologiques spécifiques à un emplacement est importante dans l'application de pesticides par voie aérienne lorsqu'on vise une efficacité maximale et qu'on veut faire une évaluation complète après pulvérisation. La présente communication décrit comment utiliser un système à minisondes mobile pour réaliser des sondages atmosphériques à basse altitude en vue d'une pulvérisation par voie aérienne. De 1981 à 1987, un total de 526 sondages par minisondes ont été réalisés dans le but de fournir de la documentation météorologique pour des essais de pulvérisation expérimentale et pour une opération d'épandage de pesticides contre la tordeuse de l'épinette au Nouveau-Brunswick. Plus de la moitié de ces sondages ont été réalisés à proximité de la piste d'atterrisage de Dunphy, et un grand nombre de ces données ont pu être comparées aux résultats d'un système élaboré monté sur une tour et exploité par le Conseil national de recherches. Les comparaisons révèlent qu'il est possible de représenter adéquatement la stabilité atmosphérique au moyen de minisondes, avec une erreur ne dépassant pas une classe Pasquill-Gifford dans 90 % des cas. En outre, les minisondes permettent de déterminer les profondeurs de brassage de façon plus satisfaisante qu'avec tout autre instrument.

INTRODUCTION

Documentation of on-site weather is important during aerial pesticide applications if maximum efficacy is to be attained and if thorough post-spray assessment is to be undertaken. Documentation can range from simple surface measurements supplemented by records of visual observations to elaborate and detailed measurements from towers extending to well above the level of spraying operations. The former are inadequate; tower-based observations, on the other hand, are usually prohibitively expensive and — more to the point — confined to sites where the towers have been erected and instrumented, and are limited to the height of the towers. Mobility is required for the documentation of wide-ranging operations such as spruce budworm spraying, and the needed mobility can be achieved in three ways: measurements from aircraft, tethered balloons, or free-rising balloons — each of which also overcomes, at least to some extent, the height limitation.

Since 1981, extensive meteorological documentation was obtained from a site near Dunphy Airstrip in central New Brunswick (Fig. 1) in conjunction with experimental trials of spray drift and deposit, employing a 65-m tower, and both free-rising and tethered balloons. This paper focusses on the exercises involving free-rising balloons, considers some comparative results, and discusses the special aspects of employing the method for operational spraying conditions. The study uses data selected from

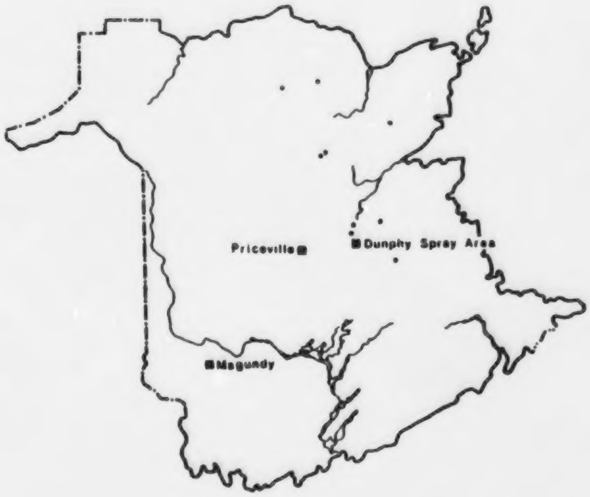

FIGURE 1: SITES USED FOR MINISONDE OPERATIONS IN NEW BRUNSWICK, 1981-87.

526 balloon ascents, each of which incorporated measurements from a temperature-sensitive radio transmission package (minisonde) and were tracked by two theodolites for determining wind speed and direction. Some of the data used were collected from sites other than that at Dunphy (Table 1 and Fig. 1). Comparative tower data are available in about half of the cases; there were no comparative data in other cases — including 65 ascents conducted in direct support of operational insecticide sprays.

TABLE 1: Minisonde operations in support of spruce budworm spraying trials and operations in New Brunswick, 1981-87.

Year	No. of ascents	Site	Comments
1981	85	Dunphy	Spray drift and deposit trials
1982	38	Magundy	Operational experiment (chemical insecticide)
	69	Dunphy	Spray drift and deposit trials
1983	62	Priceville	Operational experiment (chemical insecticide)
	64	Dunphy	Spray drift and deposit trials
1984	52	Priceville	Operational experiment (chemical insecticide)
	50	Dunphy	Spray drift and deposit trials
1985	36	Various	Operational experiments (airborne drift)
1986	29	Various	Operational experiments (chemical insecticides and Bt)
	35	Dunphy	Spray drift and deposit trials
1987	6	Dunphy	Experimental spray (pheromone)

METEOROLOGICAL PARAMETERS RELEVANT TO SPRAYING

Factors affecting the efficacy of spraying operations may be separated into those related to deposition and those related to the biology (development and behaviour) of the target insect. Both factors are sensitive to meteorological conditions, but this paper considers only the conditions affecting deposition. Although a small fraction of emitted spray material remains airborne long enough to drift well beyond the spray target, and thus pose a potential environmental hazard, we consider only target-related conditions at the time of, or shortly after, spraying.

The droplet size distribution of insecticide spray emitted from an aircraft is controlled largely by nozzle design and configuration, and is altered by evaporation after release. The preponderance of droplets are less than 100 μm diameter (Picot *et al.*, 1986), with terminal velocities so low that atmospheric turbulence is required to deliver the insecticide to the forest. In an ideal situation the aircraft can fly low enough that its wake turbulence will accomplish this delivery; usually, however, the initial spray cloud depends on some background atmospheric turbulence to assist the deposit (Picot *et al.*, 1986). Thus the atmospheric parameters needed are those related to evaporation and turbulence, with the latter being of greater importance.

TURBULENCE MEASUREMENT

Turbulence is rarely measured directly, but rather is expressed as stability parameters, where stability relates to the resistance of the atmosphere to vertical motion. The forces contributing to instability are two: buoyancy and mechanical mixing. Buoyancy (or thermal instability) relates to the vertical temperature gradient, which in its neutral state is −0.0098 °C/m. This gradient, the negative equivalent of which is the dry adiabatic lapse rate, represents the rate at which a rising parcel of air will cool due to expansion as it rises to a lower pressure level (assuming no condensation occurs). If the background lapse rate is greater, rising air parcels are warmer than their surroundings (and therefore buoyant), and the environment is considered unstable. This component of stability may be determined solely by measuring the vertical temperature profile.

Mechanical mixing results either from the flow of air over a rough surface (frictional) or from wind shear, and may occur even in a thermally stable environment. Determination of this component of stability requires measurement of wind speed and the vertical profile of wind velocity.

The forces contributing to instability interact. If mechanical forces cause a layer of the atmosphere to be well mixed, the temperature gradient will tend toward the neutral value. If, for example, a superadiabatic temperature gradient has become established near the ground as a result of strong solar heating, an increase in wind will decrease the gradient to near neutral. Likewise, a steep pre-dawn temperature inversion will be reduced to a nearly neutral state by strong wind. For these reasons, thermal stability alone is not adequate to determine the overall stability condition of the atmosphere.

Tower measurements of stability condition, where the top and bottom of a layer are precisely determined and wind and temperature are precisely and continuously measured, are highly dependable. At Dunphy the National Research Council (NRC) used a directional bivane for wind measurement so that momentum forces could also be incorporated into the determination of stability. During the last two field seasons, the NRC used fast-response thermometers to obtain heat-flux data which further improved the stability determination.

STABILITY ESTIMATORS

The most common parameter for estimating turbulence is the Richardson number Ri, defined as

$$\mathrm{Ri} = \frac{g(d\theta/dz)}{T(du/dz)^2} \qquad \text{(Rosenberg } et\ al.\text{, 1983)}$$

where

g is the gravitational acceleration in m/s^2,
T is the temperature in °K,
θ is the potential temperature (i.e., T reduced to a pressure of 100 kPa) in °K,
$d\theta/dz$ is the vertical gradient of potential temperature in °K/m, and
du/dz is the vertical gradient of mean horizontal wind speed in m/s per m.

Negative values of Ri imply instability, and positive values imply stability; Ri values near zero, specified by Sedefian and Bennett (1980) as the range −0.275 to 0.089, imply neutral conditions. More complex descriptors of stability incorporate the roughness characteristics of the underlying surface and the relative values of transfer coefficients for heat and momentum, requiring separate measurement of the vertical component of the wind speed and coincident measurement of the temperature gradient. Such detailed measurements are possible only with tower assemblies. As previously mentioned, the data collected at Dunphy by the NRC provide this level of sophistication in stability measurement (Crabbe *et al.*, 1982; Crabbe *et al.*, 1983; Crabbe *et al.*, 1984; Crabbe and McCooeye, 1985; Crabbe, pers. comm., 1986).

In the absence of a suitably discriminating description of the wind velocity profile, stability may be expressed with respect to only the temperature profile. Strictly speaking, the "neutral" condition exists only when the temperature gradient is exactly −0.0098°C/m. In practical terms, however, a narrow range of temperature gradients bracketing the neutral value is warranted for defining the "neutral" condition, and ranges of temperature gradient are similarly warranted to describe degrees of "stability" and "instability." The U.S. Nuclear Regulatory Commission (Sedefian and Bennett, 1980) developed a scheme to relate temperature gradient (ΔT/Δz) to the commonly used Pasquill-Gifford classification (Table 2). In categorizing stability conditions at Dunphy, the NRC used this nomenclature although, of course, wind-profile and heat-flux data were used along with temperature gradients in the determinations.

TABLE 2: Relationship between Pasquill-Gifford Stability Classes and temperature gradients (after Sedefian and Bennett, 1980).

Pasquill-Gifford Stability Class	Description[a]	Temperature Gradient (°C/m)[b]
A	Very unstable	$\Delta T/\Delta z \leq -0.019$
B	Moderately unstable	$-0.019 < \Delta T/\Delta z \leq -0.017$
C	Slightly unstable	$-0.017 < \Delta T/\Delta z \leq -0.015$
D	Neutral	$-0.015 < \Delta T/\Delta z \leq -0.005$
E	Slightly stable	$-0.005 < \Delta T/\Delta z \leq 0.015$
F	Moderately stable	$0.015 < \Delta T/\Delta z \leq 0.040$
G	Very stable	$\Delta T/\Delta z > 0.040$

[a] The qualitative descriptions are provided to facilitate comparisons with NRC data.

[b] The definition was modified slightly by moving the = sign to the low side of the temperature-gradient ranges in order to have the neutral value, −0.0098, fall nearer the middle of the neutral range.

METEOROLOGICAL ESTIMATES FROM MINISONDE MEASUREMENTS

The problem with tower measurements, as previously mentioned, is that they are confined to the location and height of the tower. Minisonde operations overcome this constraint. But how well do minisonde measurements estimate turbulence? The limitations are outlined below:

1. The temperature obtained from the minisonde is quite imprecise. First of all, the sensor, a bead thermistor, is less sensitive than the sensors in tower assemblies used in turbulence studies; secondly, just prior to each ascent, the sensor output must be calibrated against a standard calibration probe, whose response characteristics are different from that of the minisonde sensor; thirdly, precision is limited by the grid density of the strip chart on which the minisonde temperatures are output (Fig. 2).

2. The height precision is limited by the precision of the theodolite readings by the two observers as they attempt to follow an erratically moving target. Further, the balloon rises unsteadily, so that the height intervals are inconsistent in space and between successive ascents.

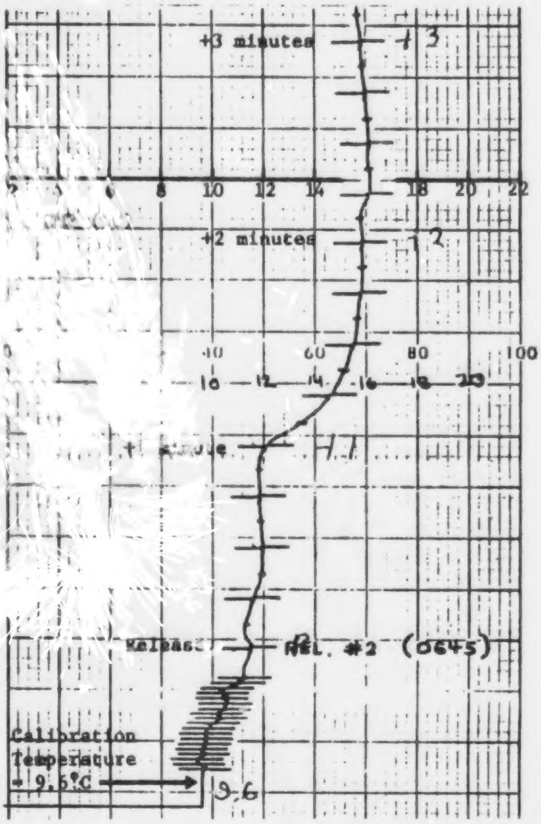

FIGURE 2: TEMPERATURE TRACE PRODUCED BY THE AERO-AQUA MINISONDE RECORDER. WIDE TIME TICKS ARE PRODUCED BY THE RECORDER AT 15-S INTERVALS. NARROW TICKS AT INTERMEDIATE TIMES ARE ADDED BY HAND DURING ANALYSIS.

3. Height discrimination is limited by the balloon's rate of rise and by the theodolite-observation frequency. This is especially critical for the determination of wind velocity, as the wind can be expressed only as the mean for a layer between successive levels of observation — unlike the temperature which is portrayed as a continuous line trace.

4. Theodolite measurements cannot be made from within a forest. Line-of-sight observation of a rising balloon being carried by wind toward the horizon requires that a clearing be found near the site where the data are to be applied. This imposes

   (a) a potential error due to geographical separation; and

(b) an error due to the non-representative surface above which the observations are taken.

The manner and success of dealing with these limitations are outlined in the sections which follow. A more complete description of operating procedures may be found in Steeves and Dickison (1986).

Height Discrimination

To improve the height discrimination the minisonde system as received from the supplier was modified by reducing the rate of rise to approximately 100 m/min and decreasing the observing interval from 30 s to 15 s. This resulted in height intervals of approximately 25 m for wind velocity determination. The use of two theodolites allowed the rate of rise to be determined separately for each layer, providing much greater accuracy than is possible using a single theodolite and an assumed rate of rise.

Temperature Measurement and Profile Determination

Fig. 2 shows the type of temperature output available from the minisonde system (Aero-Aqua Inc.). A very discriminating eye is required to estimate temperature to the nearest 0.1°C. Since the temperature must then be related to height using theodolite measurements, the estimate is subjected to further potential error. In an absolute sense, temperature estimates probably err by 0.5°C or more in many cases. In a relative sense, during a single ascent, it is apparent that better discrimination is achieved in determining temperature gradients. For example, some assessment may be made from Fig. 3, where the temperature from a series of minisonde ascents on 29 June 1987 is shown in relation to the neutral temperature gradient (dry adiabat). Once a downward flux of radiant energy becomes well established, temperature gradients, measured from the minisondes, parallel the neutral gradient almost perfectly above the superadiabatic surface layer. The layer of most concern for spraying operations, however, lies within about 50 m of the ground, where a wide range of temperature gradients is experienced, and where near neutral conditions are transitory. A time-trend analysis of stability within the layer 25-75 m above ground, for the ascents on 29 June 1987 (Fig. 4), shows that stability changed from slightly stable to unstable in less than an hour, considered by Steeves (1985) to be quite characteristic of early morning conditions. During a single spray operation significant changes in stability might be experienced.

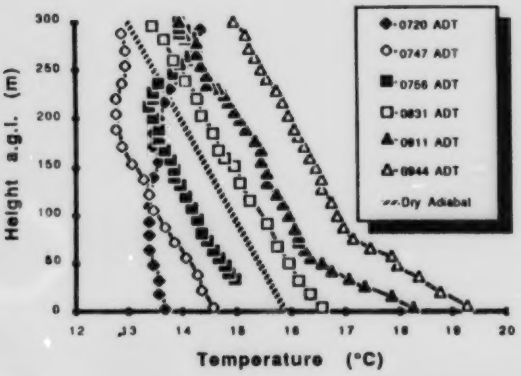

FIGURE 3: VERTICAL PROFILES OF TEMPERATURE OBTAINED FROM MINISONDE SOUNDINGS DURING PHEROMONE SPRAY TRIALS NEAR DUNPHY ON 29 JUNE 1987.

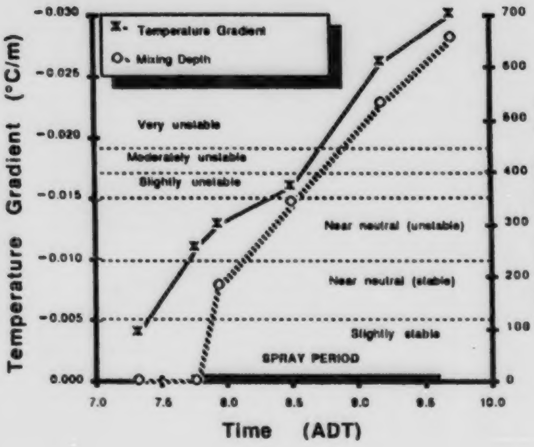

FIGURE 4: TIME VARIATION OF TEMPERATURE GRADIENT WITHIN THE LAYER 25-75 M ABOVE GROUND, AND OF DEPTH OF THE SURFACE-BASED MIXED LAYER, OBTAINED FROM MINISONDE SOUNDINGS DURING PHEROMONE SPRAY TRIALS NEAR DUNPHY ON 29 JUNE 1987. SEE TEXT FOR DESCRIPTION OF STABILITY CLASSES.

Representativeness of Temperature Measurements

The need to operate from within cleared areas introduces a potential bias in temperature measurements (in terms of being representative of conditions above forest stands) due to the nature of the surface. Because advanced forest regeneration within a clearing reduces the difference in surface conditions, recently cleared areas with large expanses of bare ground should be avoided

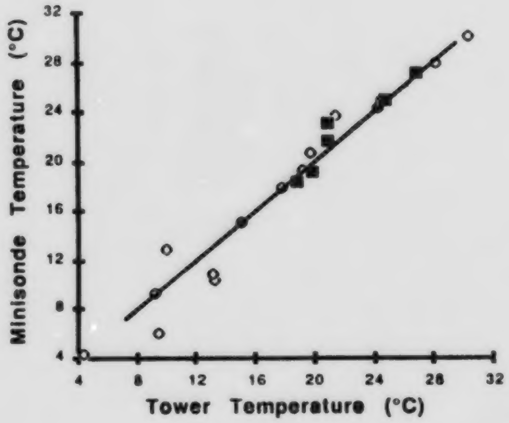

FIGURE 5: COMPARISON BETWEEN 25-M TEMPERATURES RECORDED BY MINISONDES AND THOSE RECORDED ON THE NRC TOWER AT DUNPHY. SOLID SYMBOLS INDICATE THE USE OF 10-M TOWER DATA IN CASES WHERE 25-M DATA WERE NOT AVAILABLE. LINE SHOWS 1:1 CORRESPONDENCE.

if possible. If the cleared areas are not expansive, mixing of the air with that passing over the area from surrounding forest will eventually produce a representative condition. We have generally ignored minisonde temperatures measured at release height and have arbitrarily chosen 25 m above ground as the representative level. As shown in Fig. 5, this seems to correspond well with temperatures measured from the NRC tower at 10 m and 25 m. In this case the minisonde site was within 2 km of the tower site. In the documentation of operational spray trials the minisonde site was usually more distant from the spray operation.

Representativeness of Temperature-Gradient Measurements

Fig. 6 shows a comparison between temperature gradients measured by the minisonde and gradients from the NRC tower for 25 cases corresponding to spray occasions. For the minisonde data we used the mean of two ascents, usually one at the beginning of the spray (and the NRC sampling period) and another about 20 min later. The NRC sampling period ranged from 10–30 min, depending on the nature of the spray trial. (Mean values, for both minisonde and tower data, are used in comparing measurements for all parameters.) Temperature-gradient data were not available from the NRC report for the 1981 trials. The layer used for the tower data was 24–46 m for 1982–84 and 19–62 m for the 1986 trials. The 25–75 m layer from the minisonde profiles was used for the comparison. There is obviously a slight bias toward less steep gradients measured by the minisonde in unstable conditions, perhaps entirely due to the greater range used to determine the gradients. The significance of the "errors" involved in using minisonde data can be realistically assessed only by evaluating the effect on stability classification. This will be considered in the next section.

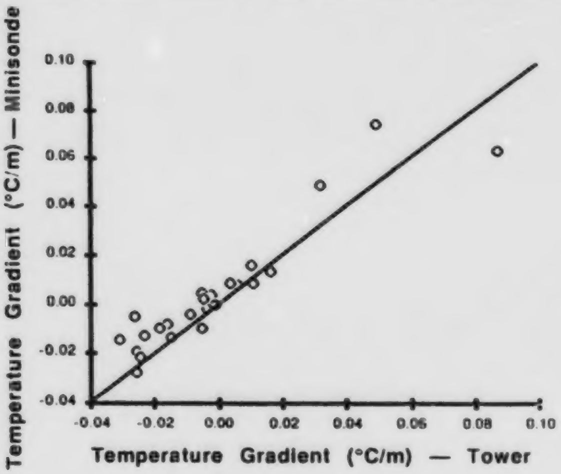

FIGURE 6: COMPARISON BETWEEN TEMPERATURE GRADIENTS (25–75 M) RECORDED BY MINISONDES AND THOSE RECORDED ON THE NRC TOWER AT DUNPHY (24–46 M AND 19–62 M). LINE SHOWS 1:1 CORRESPONDENCE.

STABILITY ESTIMATES FROM MINISONDE MEASUREMENTS

Attempts to calculate Ri values from minisonde measurements by incorporating wind velocity gradients produced no satisfactory results. Mean velocities through layers of about 25 m thickness mask the necessary profile detail. Furthermore, the structure of the clearings from which the measurements were taken was much more irregular than that of the surrounding forest, causing erratic balloon motions in the first 15 s or so after release. These structural influences within clearings seem to be a greater problem than the influences of thermal differences. Estimates of stability, however, may be made using only the temperature gradient.

We used the relationship presented in Table 2 to obtain estimates of stability class from minisonde temperature gradients. Table 3 compares these estimates with classifications provided by the NRC reports and personal communications from Dr. R.S. Crabbe. The 1982 cases (Crabbe *et al.*, 1983) were classed more broadly (only as "stable," "neutral" or "unstable") than in other years, so these were modified by using a relationship with the Obukhov length scale L, according to a relationship given by Holtslag (1984). It is reassuring that only three of the cases presented in Table 3 differed by more than one category, and two of these were cases where Holtslag's criterion had been used to modify the NRC classification.

TABLE 3: Relationship between stability classes determined from minisonde measurements and those determined from NRC tower data.

	Stability Classification Based on Minisonde Measurements						
NRC Stability Class	Very Unstable	Moderately Unstable	Slightly Unstable	Neutral	Slightly Stable	Moderately Stable	Very Stable
Very Unstable							
Moderately Unstable	1		2	1			
Slightly Unstable	2			3			
Neutral				4	3		
Slightly Stable					7	1	
Moderately Stable					1	1	1
Very Stable						3	

CONCLUSION

A review of meteorological data obtained using minisondes, and a comparison of these data with others collected from an elaborately instrumented tower, indicates an encouragingly high degree of reliability. This suggests that the use of minisondes to monitor operational aerial spraying is a satisfactory alternative to other, more expensive or less mobile, means. Another alternate, employed in the Dunphy trials and recognized as providing high quality information, is the tethered balloon system (Mickle *et al.*, 1984). Tethersondes can obtain data at greater heights than towers and — unlike minisondes — can provide continuous data at a fixed height. They can also be launched from within a very small cleared area. On the other hand, tethersondes cannot be launched during wind speeds above a moderate threshold, especially from within forested surroundings. The lack of continuous measurements at a height can to some degree be overcome by sequential minisonde releases, which can be accomplished by an experienced team at intervals as short as 15 min.

The particular advantages of minisondes are their mobility and their much greater height capability. Set-up time at a previously established site is in the order of half an hour. When commercial power is available, automated data handling procedures allow information to be produced in the field within an hour of completing the soundings. Minisonde data from greater heights allow detection of elevated inversions and determination of mixing depths, enabling reflection of the upper boundary of the spray plume to be incorporated into applications of dispersion models (Picot *et al.*, 1986).

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BIOLOGICAL INTERFACE — INSECTICIDES, INSECTS, AND POST-SPRAY WEATHER

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ABSTRACT — It is not enough to know when the target insect is in the right stage and what kind of weather is best to deliver the right sized spray droplets to a crop to be protected. It should also be determined what the insect is doing at the time of treatment because it can affect its vulnerability. Insect behaviour is affected by temperature, light, moisture, wind, and rain, all components of weather that can affect vulnerability during and following treatment. It is postulated that post-spray weather can account for a large part of the discrepancy between deposit and kill through its effects on insect behaviour.

RÉSUMÉ — Il n'est pas suffisant de savoir le stade de développement de l'insecte visé et les conditions météorologiques idéales pour déterminer la dimension optimum des gouttelettes lors des arrosages en vue de protéger une culture. Ce que fait l'insecte au moment de l'arrosage doit également être déterminé car sa vulnérabilité peut en être affectée. Le comportement de l'insecte est influencé par la température, la lumière, l'humidité, le vent, et la pluie, tous des facteurs météorologiques pouvant influencer son niveau de vulnérabilité durant et à la suite du traitement. Il est postulé que les conditions météorologiques après arrosage, par leurs effets sur le comportement de l'insecte, expliquent en grande partie l'écart entre le dépôt d'insecticide et le niveau de mortalité.

INTRODUCTION

A pesticide is of little practical use in a place other than where the target pest is found. Nonetheless thousands of dollars and kilograms of pesticides are wasted every year simply by missing the target. Textbooks tell us we can use stomach insecticides against chewing phytophagous insects but not against sucking insects, and that contact insecticides work well on both types of insects, especially the more mobile types that are likely to contact the insecticide if it doesn't contact them first. Systemics are used only in special situations against some sucking insects and internal parasites where their ultimate fate is closely controlled. These are the basic principles for the use of insecticides.

A second level of consideration is that of the stage of the insect. If an insect has a cryptic stage and an exposed stage, it is better to wait for the exposed stage if it doesn't result in an unacceptable crop loss. It is usually better to attack the insect as an active larva or nymph, than as a less vulnerable egg or pupa. Only active insects can ingest insecticides and active insects are more likely to contact insecticides. Most of us instinctively direct our control effort at the most obvious, damage-causing stage.

A third consideration, usually ignored, is the short-term change in activity of the target stage. This, and the implications for success or failure of a spray application, is the topic I will address. Dr. I.W. Varty of the Canadian Forestry Service, now retired, coined the term "biological interface" to describe this aspect of insecticide-insect interaction. In the context of spraying, the biological interface is defined as "the relationship between droplet distribution and the biological characteristics of insect and [plant] which influence toxic contacts" (Varty and Nigam 1985). As a biologist, I will concentrate more on the characteristics of the insect and its habitat than on the nature of sprays, but the better the spray accounts for the characteristics of the insect and its habitat, the more successful a spray operation will be.

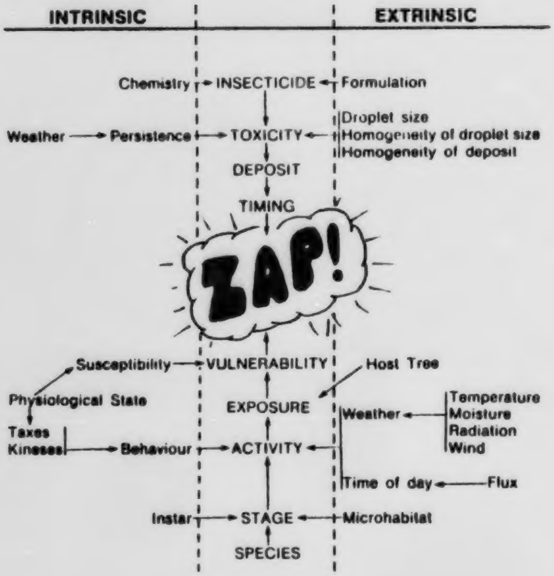

FIGURE 1: SIMPLE REPRESENTATION OF THE RELATIONSHIPS BETWEEN SPRAY CHARACTERISTICS AND INSECT BEHAVIOUR, AS THEY ARE AFFECTED BY INTRINSIC AND EXTRINSIC FACTORS.

A simple diagram such as Fig. 1 will explain. An insecticide at the top is being directed at an insect at the bottom. The attributes of the insecticide that influence its effectiveness are in turn affected by many other factors that are obvious to most of us. Likewise, the vulnerability of the insect is influenced by its stage, which influences its activity, and hence its exposure to the insecticide. The activity of the insect relates to its instar, its degree of development within the instar, its microhabitat, and its behaviour. Behaviour in turn is influenced by intrinsic mechanisms shown on the left influenced by the physiological state of the insect, and extrinsic factors shown on the right, which interact.

To illustrate the principles involved, one could select any insect commonly sprayed from the air: the migratory locust, the cotton bollworm, or the codling moth, but I know the spruce budworm best.

THE SPRUCE BUDWORM

The life history of the spruce budworm, *Choristoneura fumiferana* (Clem.) is well known. After the needle and bud mining of the 2nd and 3rd instars, on balsam fir, *Abies balsamea* (L.) Mill., the larva builds a shelter of needles tied together with silk. As Craighead (1924) wrote, "...the caterpillars... conceal themselves and remain concealed through all stages, as long as the developing foliage permits. As the new growth becomes from one to one and one-half inches long and the caterpillars are in the fourth and fifth stages, they begin tying the tips of several twigs [shoots] together. In the latter stages this nest is quite pronounced. White spruce [*Picea glauca* (Moench) Voss] offers much better concealment than balsam or the other spruces until the needles mature and spread, consequently the caterpillars are much more difficult to find on this tree than on balsam or the other spruces." Indeed this is the target at which we direct our sprays, an apparently discouraging prospect because the larva is almost totally hidden from view. The target is hardly less cryptic than the needle and bud-mining 2nd and 3rd instars, which can be completely accommodated by the mine (McGugan 1954). The best description of the shelter of the 6th instar in its final manifestation is that of Gibson (1925). "As the larvae develop they bite off the needles at their base, attach the needles, so cut off, loosely together with silk to form a shelter in which the larva lives. The shelter is attached to the twig and intermingled with the detached needles are the brown faeces of the larvae. As the larvae continue their destruction, further needles are attached to the loose shelter until the twigs are ensheathed in a loose mass of dead needles, frass, bud scales, etc., the whole presenting a reddish-brown appearance."

Why then is the spruce budworm larva vulnerable to sprays? The key is the behaviour of the larva. The early needle and bud mining stages construct a tube of silk outside the mine and attach it to adjacent needles. The larvae do not spend all their time in the mine. They leave the mine to drop faeces, which normally drop free, although some may be retained in the silk. The shelter of the 4th to 6th instars is actually a silk tube, a complex structure consisting of a densely constructed inner part, within silk-secured needles, that virtually obscures the larva, and an outer loosely constructed web of silk. The outer part becomes looser the farther it is from the inner dense tube, and it extends as far as the larva forages. The larva, by the structure of its legs and prolegs, is morphologically adapted to live on this lattice of silk and would be relatively awkward without it. This is known and taken for granted by entomologists familiar with the spruce budworm, but it has not been written down.

The behaviour of the larvae can be explained in terms of their basic responses to their environment. Second-instar larvae emerging from hibernacula are positively phototropic (attracted to light) which causes them to move to the ends of the shoots (Wellington 1948a). They may emigrate by ballooning on silken threads (Miller 1963), as did many hatchlings 10 months earlier (Eidt 1969), or begin to feed. Feeding is prompted, at least in part, by chemical stimuli, which helps account for the decreasing order of attractiveness of staminate flowers, expanding vegetative buds (Heron 1965), and old needles, but also by hunger. Hunger can cause larvae to become photonegative (Wellington and Cameron 1947). A combination of other basic responses, whose interactions are not fully understood, may be involved. Relative humidity or, more precisely, saturation deficiency or rates of evaporation (Wellington 1950a), temperature of the habitat (Wellington 1950b), and radiation which can result in internal larval temperatures as high as 3.7°C above ambient (Shepherd 1958), are some of the factors to which the larvae respond. All of these are influenced by weather.

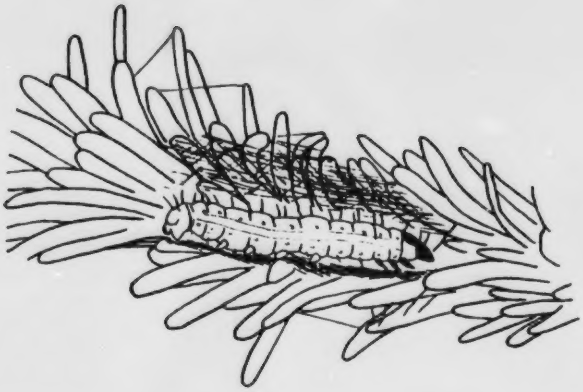
FIGURE 2: NEW 6TH-INSTAR SPRUCE BUDWORM SHELTER BETWEEN TWO SHOOTS OF BALSAM FIR. ONE SHOOT REMOVED TO SHOW DENSE SILK TUBE AND SOME OF THE PERIPHERAL SILK STRANDS.

Thigmotaxis, which is the reaction to contact, is extremely important to spruce budworm larvae. It is this response that dominates the burrowing tendency of many insects, including the needle-mining habit of the 2nd and 3rd instars. Like all apparently naked caterpillars, the small larvae bear numerous setae on all sides of each segment. Each seta has sensory cells at its base so that the insect is aware of things touched. The needle mine and the adjacent silk tube are approximately the same diameter as the larva, not measured through the body proper, but from the tips of the setae on one side to the tips of the setae on the other side. Thus through the stimulation of as many tactile sensilla as possible, the insect becomes quiescent within its refuge. Other stimuli induce the larva to feed, to spin silk, and to turn within the mine. Only overriding stimuli will induce the larva to leave the mine and the associated silk tube for the lightly silked outer habitat.

Thigmotaxis is also one of the factors to which the larger larvae respond when they build the tightly constructed silk tubes. Like many caterpillars, spruce budworm larvae leave a thread of silk wherever they go, and Wellington (1949) noticed in studies of basic temperature and humidity responses that where there was a silk trail, larvae followed it. In moving about on foliage, larvae build a loose lattice of silk on which they depend for support. On expanding foliage, the needles are silked together, the silk shrinks as it sets, and the needles are drawn together to form the characteristic shelter. The 6th-instar larva typically silks two or more shoots together to form a feeding tunnel (Miller 1963). The interior of the shelter is densely lined with silk and the basal end leads to a region of open webbing. The larva is usually oriented so that its head faces the tip of the branch. After securing needles with silk, it cuts them at their bases and eats them from the basal end. Uneaten needle tips turn brown, thus giving the shelters of late instar larvae the reddish brown appearance mentioned by Gibson. Frass is ejected at the other end of the shelter, and most of it falls free. This basic structure is modified according to the morphology of the shoot, which in turn varies according to the host species, the maturity of the tree and the foliage, and the modification of the foliage by previous years' and current feeding by competing larvae.

Several intrinsic and extrinsic factors interact to affect the behaviour of the larva within the shelter. Hunger and the thigmotactic response continue to be important throughout the larval stage. Temperature and moisture may be the dominant factors influencing the position of the larva in the shelter because microclimatic conditions are strongly influenced by the shelter. The temperature of the shelter may be as much as 7°C above ambient due to radiation by day and 3°C below due to respiration by foliage at night, and the temperature of the insect may be higher than that of the parts of the plant on which they feed. Shepherd (1958) found a direct relationship between radiation intensity and the excess temperature of the larva over ambient. The excesses were as high as 3.7°C, although they were reduced by the square root of wind speed above 1.2–1.3 km/h. The excess is related to the albedo of the insect, which becomes less important as the larva retreats into the shelter. The temperature of conifer flowers may be even higher than that of foliage (Wellington 1948b, 1950b). Temperature determines the metabolic rate in cold-blooded animals, thus budworms develop faster when there is greater radiation, as on clear days, although the ambient air temperature may be the same as on overcast days. The difference in development rates has been demonstrated in an unpublished experiment of mine.

Moisture seems to be the most important of all the physical factors. Larvae become sluggish or immobilized at low rates of evaporation at temperatures between 10 and 38°C (Wellington and Cameron 1947). Larvae were shown experimentally to avoid places of high evaporation which effectively keeps larvae in places of low evaporation, namely within the shelters. The natural feeding tunnels of 6th-instar larvae have rates of evaporation nearly identical with the preferendum (Wellington 1950a). The interaction among responses to evaporation rates, temperature, point-source light, and hunger is discussed by Wellington and Henson (1947), but the complete picture is not yet understood. It is clear, however, that hunger plays a role in overcoming the response to moisture, allowing the larvae to feed, although to do so does not require the larva to leave the shelter. When necessary, the larvae will extend the outer lighter silked habitat. Larvae ready to defecate must also move to the outer habitat to allow the faeces to drop free. This would require interaction between the physiological state of the larva, and the influence of extrinsic factors such as evaporation rate. The roles of contact moisture and wind in behaviour and development have not been investigated, nor has the apparent change in larval behaviour that causes disturbed 6th-instar larvae to drop on a thread rather than retreat into the shelter.

THE BIOLOGICAL INTERFACE

Irving (1985) wrote that budworms, living as they do in a protected environment, contact spray when they wander outside the shelter to extend the webbing. Thus it was reasoned that active spruce budworms are more likely to contact spray droplets and that droplets that impinge on the needles, buds, and silk webbing are more important than those that impinge directly on the larvae.

Aerial spraying, as it has been practiced in the past, is a rather blunt instrument. It should be possible to exploit knowledge of larval behaviour to achieve greater efficacy. To this end researchers are asking questions about the influence of weather during and after sprays on efficacy as mediated by larval behaviour, not just by residue persistence. It can be postulated that efficacy would diminish with lower temperature (lower metabolic rate), high humidity (larvae immobile), low humidity (larvae retreat into shelter out of reach of spray), and so on.

Investigations by I.W. Varty (personal communication) suggest that late fenitrothion sprays are more effective, even though the larva is larger and dose relates to body weight. The more open shelter of large larvae, and the difficulty of large larvae concealing themselves on heavily defoliated trees, may explain this observation. Varty also found that silk tended to be added to the shelter in fine, dry, calm, weather. This seems consistent with the need of the larva to create a habitat with an optimum microclimate, particularly with respect to moisture. In one field experiment Varty found that sprays before warm calm weather were more effective. Could this have been because the larvae contacted droplets when they went to the outer habitat to spin? Whatever the mechanism, he did observe greater knockdown of larvae, extended in time, after spray with fenitrothion. His approach has been cautious because the work was done at the population level, the mechanisms can only be speculated upon, and a repeat experiment may or may not give the same results.

Instinctively one supposes that fine weather is best for spraying and dull rainy weather is worst, but it is not necessarily so. Preliminary results of field experiments in cooperation with E.G. Kettela, in which all larvae were watched, suggested that rain during or following spray application had no measurable effect on efficacy as measured by budworm kill. Varty's experiment was an aerial spray on natural forest whereas ours was a simulated aerial spray on small trees in nursery beds. Tree morphology can have a profound influence on the form of the shelter constructed, as has already been suggested with respect to tree species and degree of defoliation.

Finally, the fact that the spruce budworm lives in a habitat dominated by the presence of silk has implications for the strategy that sprayers should use. Silk is so important to the larva that it literally lives on a trellis of silk and only incidentally contacts foliage except to eat it or attach silk to it. To intercept spruce budworm larvae, my colleague, Dr. Chandra Nigam, has postulated that the most effective spray deposit would be that on the silk. He is currently testing the assumption and the implications for spray strategy (see his contribution in these proceedings). His approach involves both the spray strategy and the behaviour of the larva in its microhabitat as it is affected by weather. It emphasizes both the field and laboratory approaches. The early work of Henson, Heron, Shepherd, and, in particular, Wellington, has taken on a new importance. It should be pursued further, so that study of the biological interface can proceed apace and in a rational fashion.

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THE RELIABILITY OF THE 72-HOUR FORECASTS

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ABSTRACT — The ability to produce accurate long-range weather forecasts has long been a goal of meteorologists around the world. In the last 30 years a great deal of progress has been made toward attaining this goal. The present "state of the science" produces 72-hour forecasts as accurate as 48-hour forecasts of a decade ago. However, there are numerous problems and challenges to be addressed in order to make further improvements to these forecasts. One of the major challenges is incorporating mesoscale and boundary layer phenomena into these forecasts. This is a particular challenge in summer meteorological regimes. With new numerical techniques, improved data fields and more powerful computers, further progress is expected in the future.

RÉSUMÉ — La capacité de produire des prévisions météorologiques exactes à longue échéance a longtemps été l'un des buts des météorologues dans le monde entier. Au cours des 30 dernières années, des progrès énormes ont été réalisés dans cette voie. Dans "l'état actuel de la science", il est possible de produire des prévisions de 72 heures aussi exactes que les prévisions de 48 heures il y a une décennie. Cependant, un grand nombre de problèmes doivent être résolus et plusieurs défis doivent être relevés dans le perfectionnement de ces prévisions. Un des grands défis consiste à incorporer les phénomènes mésoscopiques et de couche limite dans ces prévisions. Ce défi est de taille notamment en ce qui concerne les régimes météorologiques d'été. Grâce aux nouvelles techniques numériques, aux zones de données améliorées et aux ordinateurs plus puissants, on s'attend à réaliser d'autres progrès dans l'avenir.

INTRODUCTION

The ability to produce reliable forecasts has long been a goal of meteorologists. This paper will give an overview of the progress over the last number of years to achieve this goal.

First, the principal components influencing the production of a forecast will be discussed. A brief history of weather forecasting achievements will be outlined. The progress in improving the weather forecasts will be shown, as well as statistics on the reliability of forecasts presently issued by the Atmospheric Environment Service in Canada. Finally, prospects for the future will be discussed.

STEPS IN THE FORECAST PROCESS

In order to forecast a parameter, the present state of the parameter is required and some understanding of the processes which affect the parameter is needed. As a result, in weather forecasting, a good observation network is needed as well as a good understanding of atmospheric processes. The understanding of atmospheric processes leads to the development of models of atmospheric phenomena which assist in defining the initial state of the atmosphere and help predict how the atmosphere will evolve in the future. This understanding of atmospheric processes leads to the development of predictive models or techniques. Prior to the mid 50's, these techniques and models were graphical. However, with the development of the electronic computer, the equations governing the atmosphere can now be solved numerically. The models in operation today have resolutions of 100 to 170 km and as many as 15 levels in the vertical.

These models use different techniques to solve the atmospheric problem. There are models which rely totally on solving the equations governing the atmosphere. Others use persistence, statistics, climatology, pattern recognition or analog methods to produce predictions. Others are combinations of the aforementioned.

The output of the numerical model is in terms of fields of various parameters such as pressure, temperature, and moisture, to name a few. The final step of the forecast process is taking the forecast field and producing a product that can be used by the client. In Canada this final step has been performed by the meteorologist. However, since January 1987 the 3, 4 and 5 day extended forecast has been totally produced by the computer at the Canadian Meteorological Centre and monitored for quality by the meteorologist in the regional weather centres.

HISTORY OF FORECAST DEVELOPMENTS

Mankind has always had a requirement to know what the weather will be like in the future. This information has been used to make decisions relating to safety and security or economic gain.

Early sailors and shepherds discovered that observing the colour of the sky and the direction of the wind would allow them to make predictions about upcoming weather. Even today most of us at one time or another have used this technique to make a short term forecast with some degree of success.

However, techniques such as this have limited usefulness and over the years more sophisticated techniques have been developed based on a better understanding of the atmosphere. Significant progress was made in the 30's and 40's in understanding atmospheric dynamics. However, it was recognized that, if the equations that governed the dynamics of the atmosphere were going to be solved, a break-through in computation was needed. In the early 50's the first numerical forecast was computed using a simplified model on the Eniac computer at the Aberdeen Proving Grounds. The first daily use of numerical forecasts on a real time basis was made in Sweden in 1954 (Cressman, 1972).

By the early 60's improved numerical methods and more computer power allowed the integration of the equations of motion as proposed by Richardson. These equations became known as the "primitive equations". Since the early 60's, improvement in the forecasts from the numerical models of the atmosphere has come from better numerical methods which reduced error and improved speed in the integrations. Faster and bigger computers have allowed better resolution and more explicit inclusion of physical processes. With the addition of satellite data such as vertical soundings, winds, cloud and moisture, a better initialization of the state of the atmosphere has been achieved. The results of these advances have been improvements in the reliability of the forecast.

RELIABILITY OF FORECASTS

Reliability of a forecast can be measured in a number of ways. In order to assess the accuracy of predicting general wind flow patterns and features such as storms, several techniques are employed. Since atmospheric wind flow patterns are generally analysed and predicted on constant pressure surfaces and expressed as the height of the constant pressure surface above sea level such as the 100 kPa field (near the surface) or the 50 kPa field (about 5.4 km above sea level), a good measure of reliability of the forecast is the root mean square (RMS) error of the height field. The smaller the error the better the forecast. Figure 1 shows the RMS error of 100 kPa height for day 3 for forecasts produced from a number of different countries. As can be seen, the forecasts from the European Centre for Medium Range Forecasting (ECMRF) are considered state of the science. Canadian forecasts would fall within the range of the four upper curves. The approximate 10 m height RMS error improvement over the last 5 years is significant. If the limit of predictive skill is the forecast time at which the prediction error amounts to 75% of the persistence error, then in Figure 2 the predictive skill for the 50 kPa height field has increased from 5 days in 1980 to 7½ days in 1985; a typical figure in the early 1970's was about 3 days. The greatest improvements have occurred during the winter and the smallest in the summer (Bengtsson, 1985).

Another measure of the error of the forecast field is the S1 score. This is a measure of the error in the atmospheric pressure field. A value of less than 25 is considered a perfect score (Cressman, 1972). Figure 3 shows the S1 score for the mean sea level pressure field forecasts produced at the Canadian Meteorological Centre (CMC) for various times over the past 9 years. Note that the 72-hour forecast in 1987 is as good as the 48-hour forecast in 1978. It is also worth noting that because of weaker pressure systems during the summer scores are somewhat poorer. Also indicated on this figure are the implementation dates of various improvements in the numerical models. Figure 4 shows forecast quality based on the S1 score for the last 30 years. The installation of bigger and faster computers over the time period has allowed the implementation of better numerical models and therefore improved forecasts.

The Canadian 3 to 5 day forecast has been totally automated since January 1987 with only monitoring by the Weather Centre forecasters. The elements in this forecast includes: maximum, and minimum temperature, categorical precipitation forecast, probability of precipitation and sky condition. Six scores are used to assess the performance of this forecast: the mean absolute error (MAE) in the maximum temperature forecasts; the percentage of the maximum temperature forecasts that do not exceed a 3 degree error (reliability); percentage of correct precipitation forecasts (percent correct); percentage of correct precipitation type forecasts (% correct type); the improvement of the forecast probability of precipitation over climatology (POP Brier Skill Score); and the percentage of correct cloud forecasts (percent correct). Table 1 shows that the precipitation and cloud forecasts are only marginally reliable being correct about 60-70% of the time. Similarly, precipitation type was correct about 73% of the time. The POP forecasts are better than using probability forecasts based on climatology through the 4th day. Reliability of the temperature forecasts was poor with a higher percentage of errors greater than 3 degrees than with errors less than 3 degrees.

THE FUTURE

The future looks promising for improvements in the longer range forecasts.

In terms of the global observation network, expansion has slowed considerably due to the high cost. The incorporation of more parameters remotely measured from existing satellites shows promise. CMC is now successfully inputting moisture parameters using cloud imagery. Several new satellite observing systems are being developed for deployment in the next decade to provide more accurate measurements of wind, temperature and humidity. However, optimism must be tempered by the fact that this work is constrained by the very high cost of developing and maintaining these systems and the long time it takes to implement them operationally (Bengtsson, 1985). Nevertheless, if ongoing improvements in weather prediction are going to continue, the development of the global observing network has to be a priority.

In terms of the great strides that have taken place in the development of the computer, capabilities have increased about 6 orders of magnitude over the last 30 years. Over the next 10 years a further increase of 2 orders of magnitude can be expected (Bengtsson, 1985).

Improvements in the numerical models are needed in the handling of smaller scale phenomena. More detailed orography is required. More effort is being devoted to improving the prediction of cloud cover and height. The need for higher vertical resolution is recognized and also for much improved representation of physical processes in the near surface layer. Finally, improved representations of both shallow and deep convection are required to produce better forecasts of clouds and precipitation (Mason, 1985).

Finally, as new methods are developed to package and distribute forecasts, clients can expect to receive forecasts more specifically tailored to their needs.

CONCLUSION

In the past 30 years the reliability of forecasts has improved dramatically; however, for some parameters there is still considerable work to be done. With new technologies in the future, we can continue to look forward to further improvements.

ACKNOWLEDGEMENTS

I would like to thank Dr. Michel Béland of the Recherche en Prévision Numérique unit of the Atmospheric Environment Service and Mr. Al Kellie, Mr. Len Feldman and Mr. Nat Yacowar of the Canadian Meteorological Centre for providing me with information and statistics.

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TABLE 1: 3-5 Day Verification Scores
National Summary
January - August 1987
(Yacowar, 1987)

	Day 3	Day 4	Day 5
Mean Absolute Error of Maximum Temp. (°C.)	3.4	3.7	4.1
Temperature Reliability (% Error 3°C.)	41	44	48
Precipitation % Correct*	71	67	64
Precipitation % Correct type**	73	73	72
POP Brier Skill	12	7	-1
Cloud % Correct	62	60	59

* values for November 1986 — April 1987.
** values for January — April only.

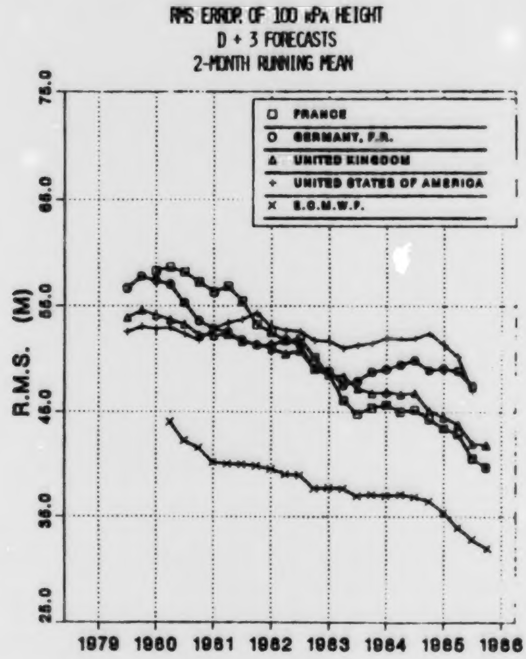

FIGURE 1: FORECAST ERROR (2-MONTHS RUNNING MEAN) AT DAY 3 FOR 100 KPA HEIGHT FIELD FOR THE NORTHERN HEMISPHERE CALCULATED FOR THE OPERATIONAL FORECASTS FROM USA (NMC), FRANCE, FEDERAL REPUBLIC OF GERMANY, UNITED KINGDOM AND ECMWF. COURTESY OF THE WMO/CBS FORECAST INTERCOMPARISON PROJECT. (BENGTSSON, 1985)

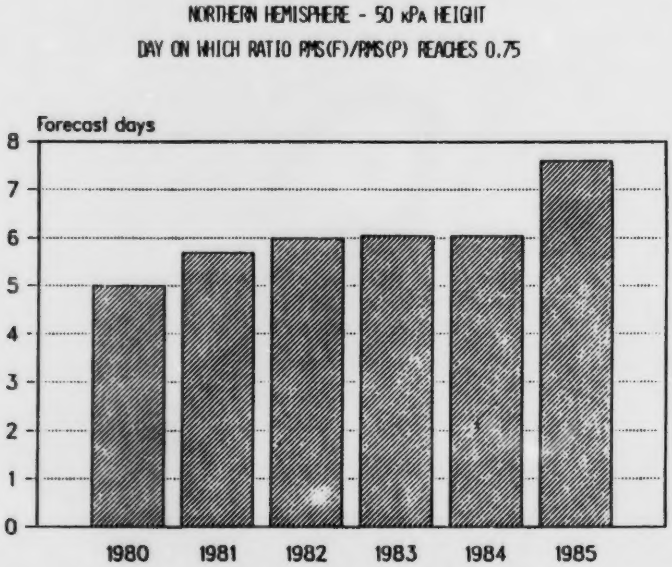

FIGURE 2: PREDICTIVE SKILL IN DAYS (12-MONTHS RUNNING MEAN CALCULATED FROM MONTHLY VALUES) FOR THE ECMWF MODEL FOR THE 50 KPA HEIGHT FIELD FOR THE NORTHERN HEMISPHERE 1980–1985. (BENGTSSON, 1985)

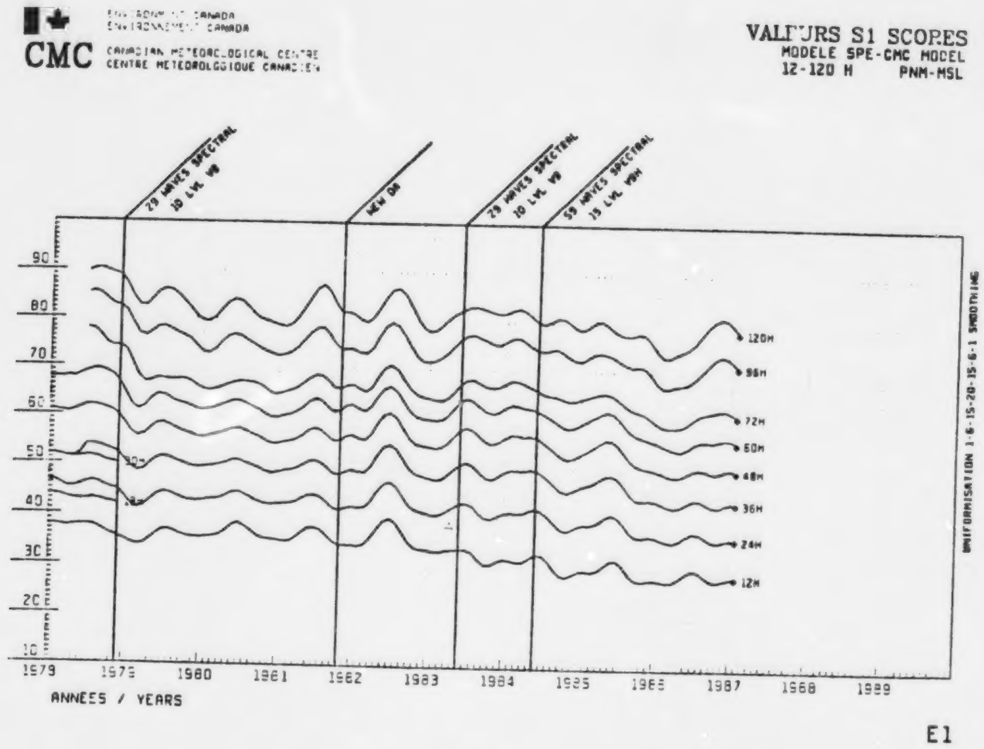

FIGURE 3

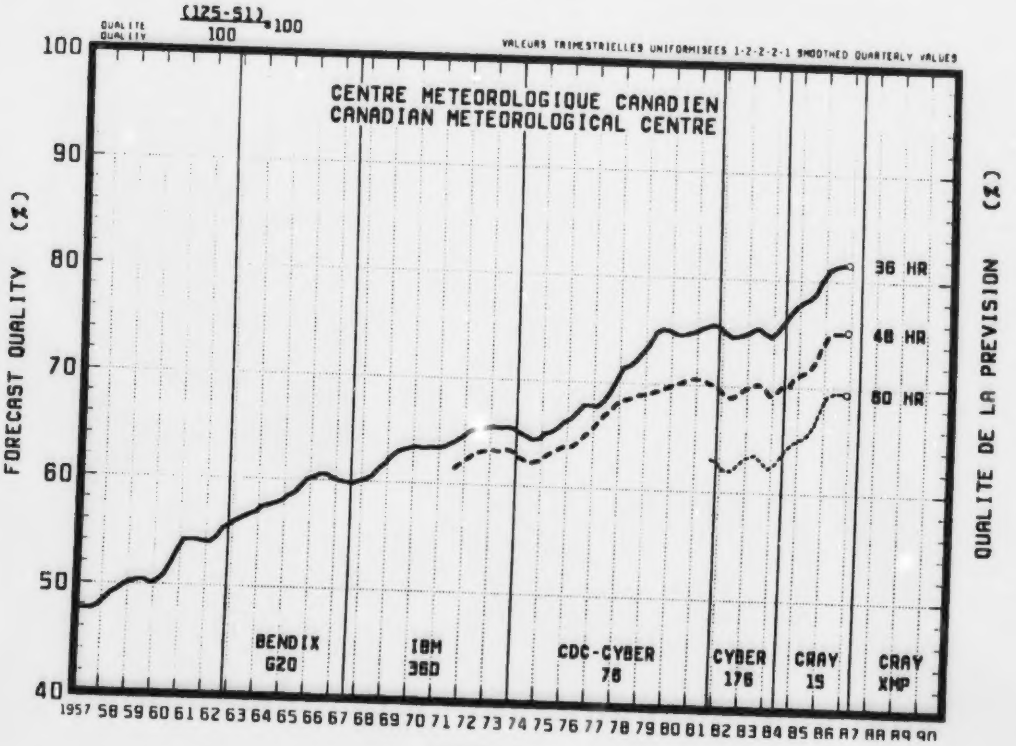

FIGURE 4

SESSION VI DISCUSSION PERIOD

Panel Chairman — H.J. Irving
Panel Members — L. Elias, R.B.B. Dickison, D.C. Eidt, W.S. Appleby

Chairman:

In posing questions to the panel, will you please come to the microphone and identify yourself and the organization with which you are affiliated. The floor is yours.

Bob Campbell:

I have a question for Dr. Dickison — I am interested in basically deciding on when spraying is going to be allowed or not, and obviously a thing like stability is something that I was interested in. From an operational point of view, probably running up balloons and having two theodolites out is not very practical. I guess the question I have is that leaves probably putting up something like a tower. How high a tower do we have to put up and what sort of money would we talk about having to come up with to be able to get, let's just say, the extreme, the very stable conditions, the things we just might want to knock something off the end, rather than being able to say well its moderately stable or neutral or whatnot.

Bob Dickison:

It's an interesting way to put it. I used the exact opposite approach in my talk — that towers are impractical and that balloons systems were. If you are always going to spray in the same place, that is the Dunphy scenario ad infinitum, sure, build yourself a tower, but if you are going to jump all over the province, as the operational sprays do, then the tower approach is more difficult, not impossible, of course, because you can mount towers on vehicles and drive the vehicle from one site to another, erect the tower and begin taking measurements. The reason that I think that that is not practical is that the height to which you would need to erect the tower in order to get the stability measurement is impractical for a mobile tower, but perhaps my NRC colleague or others could respond to that. As I mentioned in my talk, within a couple of hours we can move quickly from one site to another with the balloon system. Maybe a more practical approach could be also the tethered balloon system because you have a high initial investment but the mobility is there. What was the cost of the Dunphy tower? One million, or was it two million or something like that?

Lorne Elias:

I hope not. Dick *(Crabbe)* do you have an idea? $20,000 or something?

Dick Crabbe:

Yes, in the order of $30,000.

Bob Dickison:

Is that instrumented?

Dick Crabbe:

No.

Bob Dickison:

And the instrumentation is probably doubling the price by the time you get the sensing system and the interrogation system, right? Another possibility is to instrument an aircraft and perhaps I should have mentioned that in my presentation. When I began preparing that paper my intention was to compare the Minisonde system and the tower system with some temperature profiles determined from aircraft but when I got into the data I found that much of it was contaminated by inadequate calibration of the airborne thermometer. Forest Protection Limited instrumented a couple of aircraft in a couple of seasons with the intention of trying to test the reliability of measuring temperature profiles from the air and since the aircraft are already in the air, we are talking about instrumenting bird-dog aircraft, that seemed practical and perhaps a more careful approach to it would make it practical.

Audience (not identified):

What about a smoke generator on the aircraft?

Bob Dickison:

I think that's very practical and that was discussed a little bit two or three years ago in the NBSERG meetings, about whether putting a smoke emitter onto a bird-dog and having them fly over the spray line and watch the behavior of the smoke in advance would certainly be a highly effective visual indication of the stability characteristics.

Ron Richardson:

I'd just like to follow-up on that question. We've been talking about spraying way above forest canopy, maybe 30 metres or so, many of the herbicide applications are not sprayed over trees. They are very low to the ground in the order of maybe five metres. Could you get away with a tower much smaller, say a ten metre tower or less in that situation?

Lorne Elias:

We've done some tests related to herbicide spraying and I'm going to let my good colleague Dick Crabbe field the question for you.

Dick Crabbe:

Thank you, Lorne. Was that question directed at stability, the measurement at ten metres, for example?

Ron Richardson:

Yes, we're looking at an operational spray.

Dick Crabbe:

Well, you can mount it ten metres over flat land, simple propeller animometry with three dimensional response and correlate that with fast response thermometers to get heat flux and that would determine the stability very accurately. That's over flat land, of course, and you need some kind of logging equipment and some way of getting a 15 minute average or 20 minute average. But that's a very simple measurement. It takes a certain initial investment in equipment and certain maintenance, but it does work.

Ray Hoff:

I have a question for Dr. Elias. I was prompted to ask this question because of your profile of concentration at Kapuskasing. You reminded me of many years ago when we were working in Northern Ontario at a major international nickel company, which I won't name because I wouldn't want to embarrass the company. We had an instrument to look at Esso II profiles going over the top of us as a function of time and one day he was out and he saw a lower concentration, integrated concentration above us, and he said we must be putting out less material today and we have to convince the fellow that windspeed does enter into the measurement of mass going by a plane. And my question to you is really wouldn't it be a more appropriate profile to put up in discussing drift, downwind drift, the mass flux across that plane at a given distance rather than the concentration which is related to the windspeed?

Lorne Elias:

Yes, that's for sure. I was showing these profiles as an experimentalist. They mean more to me I suppose but the calculation can be made of the downwind flux, let's say, two cross wind planes to determine the loss of material. We haven't processed the data to that state yet but I imagine Dick *(Crabbe)* will be doing that in due course. I think the profiles, though, still indicate the situation that there is less drift with the more unstable conditions. One thing I wanted to mention, too — why we had more faith in this data, in case I didn't mention it, this data was all obtained with rotor rods so that's why we're putting more stock in it.

Dick Crabbe:

If I may I could add something to Ray's *(Hoff)* query — those three trials that Lorne Elias displayed on the screen were conducted in about the same mean windspeeds at spray height, which was 22 metres above ground over two metre vegetation. So if you compute the flux terms, the flux profiles, the only change between them would actually be the concentration profile given that the wind profiles would all be the same on each one, of course the stable conditions with slight changes in the wind profile, but by and large the changes in wind speed profiles for those three were much less than the changes in the time integrated concentrations that were shown.

Dave Maass:

The question I have is for Bob Dickison and I am wondering if you could explain quickly again how you factor in the windspeed in the stability calculations where you are only calculating temperature on the balloons, I guess you lost me there.

Bob Dickison:

My point was that we don't or we didn't. I showed you a table that related stability categories to temperature gradients. If you have good wind profile data as you would have from a tower, then you could use a more sophisticated approach by incorporating the wind factor into the determination of the stability. The point I was making was that when you cannot do that, and you cannot with a Minisonde system, how closely can you approximate it. That was the thrust of the tail-end of my talk.

John Maybank:

I was going to ask one of the speakers, possibly Bob *(Dickison)* — I seem to recall a few years back the development of LIDAR measurements for low level turbulence and probing. They were going to be used for Chinook structure measurements in southern Alberta. Now I have not heard much about this over the past couple of years, so I just wondered, not being up at all on LIDAR, whether there is anything there that can give you structural information in those 100 - 200 metre heights. The other question I have and I guess it goes to one or other of the panel here, the Forestry Service perhaps, is there any evidence with the spruce budworm of an activity change in his behavior with either pressure or humidity. Pressure presumably changes his own physical dimensions and humidity could change the silk fibre cocoon structure. Just an outside chance at something.

Bob Dickison:

I would invite Dr. Mickle, perhaps, to talk about the LIDAR approach. He's shaking his head; he's going to let Ray Hoff do it.

Ray Hoff:

There are a couple of systems out to measure temperature profiles with LIDAR and DOPLAR. They are certainly not going to be applicable for an operational environment, they are half million dollar systems. Certainly in the research situation they might provide information but for the kind of work that is being done here, or being proposed, I think that Dr. Dickison's proposal to use Minisonde's to get profiles is adequate.

Doug Eidt:

With regard to pressure and humidity and their impact on spruce budworm, on the pressure side very little is known, but I think most of us will be aware that air pressure, of course, is very important in the activity of things like black flies. When you get thunder storms coming you get increased activity, that sort of thing. There have been no experiments, to my knowledge, done to establish any kind of relationship between this sort of thing and budworm activity, but if there is a place where there would be something I would first look at adult activities and how this might be involved in triggering flight activity. Again it is likely to be one of several factors involved. Humidity is important, but as I mentioned in my talk, you have to look at it the other way around — what the budworms are most sensitive to is in fact evaporation rates, so that it is not just a question of humidity it is also a question of wind movement and various and sundry other things. Now I am not a physicist so I'm not sure what all these things are, but they are reacting to rather a saturation deficiency or an evaporation rate if you like and, of course, it's all important in the behavior of the budworms and it will effect them differently. The larvae have been studied quite intensively, not other stages. There is definitely a transition in the way larvae will behave when they get into the last instar and you see this in some of those sensational pictures they used to show of thousands of budworms that jumped out the trees and left these threads hanging down. These are last instar. They tend to abandon their shelter rather than retreat into it under certain types of disturbance. Now how this effects their reaction to moisture, I can't say. My talk was mainly a plea for the kind of investigations that would answer questions of this sort.

Bob Dickison:

Perhaps a little bit of elaboration on that should refer to the study that Dr. Nigam is involved in in monitoring larval behavior by video camera because simultaneously very detailed measurements are being made of the climate, the weather of the area where he is working, and includes relative humidity, it does not include pressure. The temperature is being measured just about every place that a camera is placed. We have temperatures being measured at four spots round in the camera sight.

Doug Eidt:

I am tempted to make one further comment Mr. Chairman, if I may, and that is one of the things that we have now that Wellington and his associates didn't have back in the 50's is the microsensors, we have more sophisticated ways of measuring these things that they didn't have and one of the things that Dr. Nigam is finding is that if you look at gross weather, mesa-climate, micro-climate, these are all relative. What do you mean by micro-climate? Do you mean the climate in that hillside or in that tree crown, where do you mean? What the budworm is responding to is the climate in that shelter that I showed you on the slide, and how do conditions there relate to the climate that you're measuring in the tree crown or in the tower, or wherever it happens to be. We don't know what these relationships are.

John Ray:

I am sure, Mr. Chairman, that you will agree with me that the panel has not answered the question — how does the man in the field decide the stability of the weather? How high has he got to measure these profiles? Would the panel please answer.

Norman Akesson:

I'm going to raise another spectra here, too. Dr. Elias, this matter of drift. We have gone backwards and forwards on that one. What defines drift, how would you establish what the bounds and limits are? I think it is very important from the standpoint of the applicator and operator that he be given a certain amount of freedom, which I refer to as extended swath versus drift. Any comment?

Lorne Elias:

You sure know how to hurt a guy. One of the problems of conducting repeated tests like this, is that we do get in a rut. You've brought up a point that has bothered me. We try to set up idealized conditions for our purposes. That is, we want the wind to be blowing orthogonal to the spray line so we can try to control some of the situation and determine the effect we're looking at. The other thing, just before I — I'm not evading your question, I want to get to it, but the other thing I wanted to mention as far as most acceptable spray whether — in my opinion anyway, I think if you are trying to localize the deposit, if at all possible you spray in the direction of the wind. I've looked at the deposit data of UNB and in those cases where the wind direction was least favorable for our purposes, i.e. large angle away from orthogonals and starting to get parallel to the spray line, the deposit densities were maximized under those conditions. How do you define drift? If you will define the fetch we might be able to define it. The type of forest we were talking about is a fairly homogeneous forest with I'd say several kilometers of fetch and the drift then — you've still got me — we at NRC are concerned not only with the operator's concerns of how much is really in the target area, we also have the concern about what drifts away to be of public concern we'll say. We worked with the New Brunswick Department of Health in helping them to establish set-back distances and taking measurements under worst case conditions, i.e. when the wind was orthogonal to the spray line. I guess within that context, that is, of these worst case conditions, if we tell them you're going to get so much loss of the pesticide, it's up to them to decide whether these dosages then are significant to the health hazard. Is that close enough to an answer?

Bob Dickison:

As an academic we look for a lot of ways of saying "I don't know". I'd like to point out a couple of important issues. This is supposed to focus on operations and as I showed you in this diagram, which was perhaps a little too complex for the time available to absorb it, you're looking at a time change of stability that required only, and I emphasize only, because an hour for an operator is a short period of time, only a period of an hour where you have neutral conditions before you get into unstable conditions. What we're trying to establish is that it would be advantageous to spray in unstable conditions or try to convince the regulators that it is OK to spray in unstable conditions. You pointed out the need to define the depths of the mixing and you'll notice it very quickly moves from zero to, how long does it take — an hour for some four or five hundred metres. What's desirable could be addressed to what I consider a good example of perfect spray weather in two of the four occasions of the work done at Priceville. This is the only meteorological data available. In 1983, the spraying was done where there was half the inversion base of sixty metres above the ground and from about twenty metres to sixty metres the atmosphere was unstable. The blue line is the neutral case and the temperature was falling more rapidly than that. This I consider to be an ideal situation where you get very vigorous mixing downward, but a strong capping inversion which restricts the off-target drift. The second case in 1984 and all of these are quite good because you have inversions here at about 130 metres and another one here with an inversion just above the spray plane with near neutral conditions below it. I think this is very useful information to the operator if the operator is in a position to be selective enough if he's only going to spray once and he has lots of aircraft available and lots of time to do it. I am sure that Dr. Picot, if he's here, would like to address the issue as well because we all recognize that you can't solve all the problems in the field and for planning we need models. So Jules, *(Picot)*, if you are here, maybe you'd like to say a word.

Jules Picot:

Well, thanks for this unanticipated opening. I guess the modelling work that we have done really matches what Dick Crabbe has found in his measurements of particles airborne in the atmosphere and admittedly we don't go down beyond 400 metres with our calculations but the models that result have shown that the cloud does not really go very high, even when the capping inversion is 400 metres above the ground. I think in almost all of the cases we are talking about, I don't think there was much more than 100 metres lofting of those particles. I agree with Bob *(Dickison)* that it is nice to have an inversion just above the spray height with lots of mixing below. Thank you.

Steve Parkin:

One of the things that I was very impressed by when I did a brief amount of work in New Brunswick a few years ago, was something that the pulp and paper industry actually does to help the operator, that is to produce a lot of smoke from their saw mills. I've got some photographs here, actually, which I was just showing a colleague of mine a few moments ago, which show an amazing amount of smoke being discharged from these mills, and some of which forms a marvelous flow of visualization for people to see what is going on in the atmosphere. One particular slide I've got shows excellent capping at a certain altitude. You could see that from miles away with actually no problem whatsoever. OK, we don't have sawmills everywhere that you spray, but if you do happen to have some nearby I'm suggesting that perhaps you ought to tell them to turn the smoke up when you are doing the spraying around there.

Gary Atkinson:

A word of encouragement to the operational types who want to know how to classify the atmosphere's stability. The original work by Pasquill-Gifford using only three items to classify stability — sun angle, the amount of cloud in tenths and the wind at ten metre height. Those are the only three that they used. Now the reference I give you for that is Turner's workbook from 1970, published by the EPA in the States, they have a good description of it in there. The second comment I want to make is to Bob Dickison and that involves capping inversions. If you had a capping inversion, at a level that was slightly above the aircraft path, I would be very concerned about any sort of lofting getting in there and being trapped in a layer, and being carried off a long way in a concentrated layer to be brought back down to the surface sometime later by the air becoming more unstable below. This is the same sort of condition we find on the Prairies occurring with stubble burning where the smoke rises from the fire, gets trapped under a layer, gets transported a long way, comes over the heat island of the city, or in the morning the insolation starts to break down that inversion and makes it more unstable below the capping layer and the smoke is brought back down to the ground. It's been quite a problem around the Winnipeg area.

Bob Dickison:

If you're dealing with a heated plume, such as you get from a fire or a stack into an inversion condition, capping inversion is based at the ground and the plume or the smoke, the affluent stabilizes and does not mix. The scenarios that I presented as being highly desirable had unstable conditions, or at least neutral conditions below, and if there is some wind then the material is being scavenged from the plume by the forest, which of course, is exactly what we want. I suppose there is a concentration below the capping inversion, but in terms of improving the delivery of the material to the forest within the target area, I guess I would hold by the thesis that that is the most desirable condition.

Chairman:

I think we have a good picture of a capping inversion if we could turn on the projector just for a second. Could we have the lights, too. Go ahead Bob *(Mickle)* while we're waiting.

Bob Mickle:

I would like to ask a question of you, Mr. Irving, as to what extent do you consider weather forecasts in carrying out your operational spray program and what spray weather would you be interested in having in a forecast. I'd then turn the question over to Bill *(Appleby)* and ask whether AES is in a position to give specialized forecasts in support of forest spraying.

Chairman:

I'll remember the question and could we have the comments on the slides and then go to that question.

Steve Parkin:

I have no real comments it was just that it might help Bob Dickison explain capping inversions while he was trying to talk about the scavenging effect really.

Bob Dickison:

That looks to me, Steve *(Parkin)*, like a heated plume and it's probably not into a capping inversion with instability conditions below it, but into a surface based inversion layer. There is a vast difference in terms of accomplishing what the sprayers want.

Bud Irving:

Thank you. To address Bob Mickle's question. The answer is at this time no, we do not give any consideration to the post spray weather. When we think that the weather is appropriate for deposit we go ahead and spray, irregardless. The second part of this, my thoughts on it — yes, I believe that the post-spray weather is very important and that we should be pursuing this and that we should develop enough confidence so that we can say "go" or "no go" on the basis of the probable effectiveness of the insecticide. I don't believe that we have the detailed information in which we have enough confidence for the sprayer to do this at this time, but I'll pass the rest of the question on to Bill Appleby and remembering that we are talking about I believe almost point forecasts over a large area, in other words, we're talking of multiple point forecasts.

Bill Appleby:

In terms of providing that sort of forecast it does become a problem, particularly in terms of the parameters that you're looking for. We, of course, do the short term aviation terminal forecasts and if you're looking for that type of a point in the short term that's one thing to provide. We already do something of that nature, it's difficult to do without observations from that specific area. As you go out in time it becomes much more difficult. Particularly if you're looking at the post-spray effects of the second or third day, as you can see our skill gradually diminishes and it gets much more difficult to provide that in the sort of detail that you'd want for say a very specific area that you'd be talking in terms of areas of 100 square kilometers, or something of that nature and that's getting pretty fine for the particular type of forecast we presently issue. In short, I guess it's something we don't have a lot of experience in providing at the moment, our second and third day forecasts are quite general. Depending on what you'd require in terms of post-spray parameters, it would be difficult for me to really say whether we could provide that.

Bill Whalen:

From a herbicide point of view it's a different thing from what Bud Irving is talking about. I think he's relating more to the insecticide spraying. We look at weather really strongly because we have to have four hours of daylight (four to six hours depending what you're using) for it to really work. We would look at the 72-hour forecast and weather in all respects because we spray in the evening, we have to have at least until dinner time the next day for the stuff to work. So the weather is very important in that respect.

Chairman:

How are you finding these forecasts for your use then, Bill *(Whalen)*?

Bill Whalen:

Thanks a lot, Bud *(Irving)!* Well, not too bad. We get all our weather from the Fredericton Airport, and I imagine it comes from the Environment people there (Atmospheric Environment Service), but I'd say 80–90%, it's really not too bad. When you're looking to three to four days down the road it's not always that good but you can usually count on a 48-hour forecast pretty well.

Bob Dickison:

I'd actually like to follow up on that a little bit because forecasting is not a one-man show and Bill *(Appleby)* would certainly endorse that, and if you're talking about how effectively to deliver something to the forest, the best forecaster may be the guy who's sitting in the aircraft ready to take-off — for a couple of reasons — he has a lot of experience with spray weather and he is there, and if you're talking about forecasting for one hour ahead, don't stand in the middle of New Brunswick forest and phone the Fredericton Weather Office or the Halifax Weather Office, but if you want to know the weather 12 to 24 hours ahead, then you need professional help. Nobody should be dumb enough to think that he could stand there with his finger in the air and look out the window and feel that he could produce a 12 or a 24-hour forecast. Even those of us who have professional forecast training are not dumb enough, in spite of any appearance that we may present, to believe that we can out-forecast the Canadian Weather Service. Maybe we can do it in a period one to three hours, and I put my reputation on the line any time in that time frame, but I am not dumb enough to think that I can out-forecast them 12, 24, 72 hours ahead. Its a far, far different game and everybody who's making use of forecast information had better realize that there are vastly different skills involved in forecasting for the next half hour, the next half day and the next half week.

Charles Wiesner:

I think I detect a little bit of confusion here. I think there is perhaps a very simple reason for this confusion. Bob *(Dickison)* in fact, in a phrase that he used just a moment ago perhaps put the finger on it. He used the term "getting the material down", (the operator getting the material down). I think part of the confusion that we're confronted with here is that we're talking about deposit and drift simultaneously because that's the way we do it in our experiments. We measure deposit, we measure drift, and we try to relate or understand the influence of various operational and meteorological parameters on those two factors, but as far as looking at the influence of weather or any other parameter on spraying, I think it would make sense to separate those two factors. It seems to me that the operator's first concern is to achieve an efficacious deposit and that's a first objective. OK, so let's look at that objective and then look at the various parameters — weather, aircraft type, vortex strength, aircraft height, and what have you, and see which ones influence efficacious deposit. That's a fairly easy one. We know a little bit more about it now because the Dunphy experiments and some of the other work that has been done, and also we have a target to shoot at. We know, we've been able to define in the last few years what an efficacious deposit is, and we can go in there, either with gas chromatography or looking at damage post-spray and see whether we have an efficacious deposit. As far as drift is concerned, that's also important but it's important for different reasons and it's perhaps of secondary importance to the sprayer's job. I'm not saying it's of secondary importance to society but it's of secondary importance to the sprayer's job. The problem with drift is that we don't have a target to shoot at. On one hand, we're saying, that we need incremental drift to get a decent deposit and I don't think anybody doubts that, so a little bit of drift is good. On the other hand we don't want a lot of drift because it is going to screw up the environment. But the environmental people, the regulators and the health people, won't give us a target to shoot at. They won't tell us how much drift is bad and without a target to shoot at, we are just sort of wandering around in circles. I think it makes us look at those two problems, not in isolation but as separate, defined objectives.

Norm Akesson:

At the coffee break Bob Dickison and I talked about another function in here which correlates these in part and I just wonder if he would say something about that, I think it might be of interest. This is, the matter of the amount of material released in a given period of time. I think this refers to what Dr. Wiesner is talking about, too. Could you comment on that a bit?

Bob Dickison:

This could be addressed by others, of course, but we were comparing the operational spraying against budworm with the herbicide spraying and Dr. Akesson mentioned the fact that one of the ways to eliminate the adverse problems is to reduce the amount of material put into the atmosphere for a deliberate purpose, and one of the things about the budworm issue that hasn't been brought up in the Symposium is that you get differential development of individual budworm by individuals, by habitat, both vertically within the tree and horizontally by aspect around the tree you get differences in development between species because the foliage emerges more slowly on the firs than it does on the spruce, and the budworm with them, and also you get differences imposed by topography. You get more development on favorably located slopes than you do on unfavorably located slopes. The point is that you can't pinpoint exactly when the budworm is ready, even if you knew by a careful study of its life cycle. So what happens operationally is that they spray twice, several days apart, and this accomplishes two objectives. It gets those budworm which were unexposed on one occasion, it gets them the second time around, or vice versa. Also, it means that they can spray with lower doses and many budworm, of course, are getting a double shot but Bud *(Irving)*, this would be an issue that you might wish to speak to us as an operator.

Chairman:

I would like to very much, but I think we are running very tight on time. I'd like to take the Chairman's prerogative and pose one question myself and that is, has anybody done a calculation as to the proportionate reduction we would have in available spray time if we were to adhere to the information that has been suggested this morning of when it is acceptable to spray. In other words, would we cut our available spray time by half or three quarters, or what would happen on this. Has anybody done anything on this?

Lorne Elias:

Can I stick my head out on this? Judging by how long we have had to wait on occasions of our spray trials for good weather, I'd say you'd cut down your window by at least a factor of two.

Bob Dickison:

I'd like to address the issue by saying that in the spray trials that if they could have moved their grids around on the advice of us meteorologists they would have had a lot more success, but they had the stupid things fixed to the ground. But, I think that the take-home message here is that sure there are certain times that it doesn't seem to be efficacious to spray, at least if we talk only about delivery of the spray materials to the forest. You would probably be advised to cut out the spraying that is done under very stable conditions and extend the spraying under unstable conditions, so perhaps there would not be any loss of time. But don't forget, I'm sure you don't forget, that there is the problem of flight safety and there is the old air force story about "old pilots" and "bold pilots", but no "old, bold pilots", but when you get very turbulent conditions near the ground, which might be good for getting the material into the forest, the pilots are not too anxious to fly as close to the ground as Jules Picot's model would tell them they should.

Bud Irving:

Thank you, Bob *(Dickison)*. I think this discussion has pretty well highlighted that we know a little bit about what we should do, we don't really know how to do it and that there is a tremendous amount of research and development that still must go into this to answer the applicator's questions and to do an effective job. I just want to highlight that we may well, taking my own situation, be wasting hundreds of thousands of dollars per day in spraying at times when we are not getting either adequate deposit, or at times when post-spray weather will negate the work that we have done. I think that we have highlighted something that we better have a look at this afternoon and in the future. In closing this session, I want to thank most sincerely all of our speakers who have done a lot of work in preparing their presentations for us and I believe have done an excellent job. Thank you, gentlemen.

SESSION VII

WRAP-UP PANEL DISCUSSION

SESSION VII WRAP-UP PANEL DISCUSSION

Panel Chairman — G.W. Green
Panel Members — A.M. Drummond, M. Pelletier, J.W. Barry, R.S. Crabbe, H.J. Irving

Chairman:

As I indicated to you in my opening remarks on Tuesday, this Symposium was conceived because the Associate Committee on Agricultural and Forestry Aviation believed that a great deal more still had to be learned of the fundamental physics and the aerodynamics involved in the aerial application of pesticides before further significant advances could be made to apply these materials from the air in a manner that would optimize targetability, effectiveness and efficiency and minimize off-target drift and environmental impact. Over the past 2½ days, an array of international experts in the fields concerned have brought us up to date on the current state of the art in the component parts of this complex problem. We have been brought up to date on the principles of spray droplet formation. We have learned of the factors affecting and governing spray cloud behaviour from the time that the spray cloud is produced until it moves into and impacts on the forest canopy. We have been informed of the techniques available for spray cloud measurement and assessment both in the laboratory and in the field. We have been exposed to current advances in our ability to model spray cloud behaviour and to simulate that behaviour using the best computer models in existence. We have had specifications for the most acceptable spray weather laid out for us. We have learned how to measure site specific weather and we know just how good 72-hour weather forecasts really are. And we have had driven home the fact that to make the most of this sort of information, we must have a much better appreciation of the biological interface involved.

I hope it is abundantly clear to every one in this room that in our quest for the knowledge that we now have, and that we will seek in the future, we are driven every bit as much by our desire to address societal and environmental concerns as we are to increase the accuracy of aerial application of pesticides and to reduce the costs involved in their use. Rod Carrow provided us with a most thought provoking and impressive opening theme address. He indicated that we must always remember that we are in the business of protecting the forest resource — we are not in the business of using either biological or chemical pesticides. I agree with this completely but perhaps from a slightly different stance. In the 1987 Lein poll referred to by Rod (*Carrow*) in which people were asked to rank the values they associated with the forest environment, those polled ranked spiritual, aesthetic, ecological and recreational values far, far ahead of economic values. That's interesting. But I'm convinced that not one of us in this room or, for that matter, any of those polled, would find much spiritual or aesthetic inspiration in the Cape Breton Highlands following its devastation by the spruce budworm some few years ago. Nor, would they be able to pinpoint any real ecological or recreational value accruing from that devastation.

I do believe though, that anyone who viewed the havoc created by the spruce budworm on the Cape Breton Highlands would have to agree that it had dire economic impact on the area. I guess what I'm trying to get at in this is that there are more reasons than economic for protecting our forest resource but the techniques for protecting it, whatever the reason, remain essentially the same. If we are to continue to use aerially applied pesticides to protect these forests, then, in my mind at least, it is imperative that we be able to account for every unit of pesticide, be it chemical or biological, that we emit from an aircraft. That accounting is basic to informed and objective decision making and to generation of public support where forest spraying operations are concerned. We have heard a good deal of compelling support over the past few days for UULV spraying with droplets in the low micron size range. What we have also seen is evidence that this might place us in a "Catch 22" situation where off-target drift is concerned. There may be ways to get around this by controlling or reducing aircraft spraying height and increasing vortex strength, but this is not without its problems also. I guess, like everything else in science, the more we learn, the more we realize that we don't know.

In this remaining session of the Symposium, our job is to review briefly where we stand in the areas concerned and to delineate and attempt to priorize what still remains to be done, who can best do it, how do we ensure continued financial support for it, and finally, how might we be able to pool our resources and our expertise to attack priority problem areas most effectively and efficiently. I'm not naive enough to think that we are going to accomplish all of this in the two or so hours remaining but I am enough of an optimist to believe that we will be able to take at least a few steps down that long and important road.

To start the ball rolling, I'll call on Al Drummond to provide an encapsulation of what we have learned from Session II, The Principles of Spray Droplet Formation. My role in all of this will be to try to keep us on time and keep some order into the rush to the microphones in the center aisle. The people up there at the front, the panel, are going to carry the ball with your help. So with that introduction, let's get at it along the lines that I described to you at the close of this morning's session.

Al Drummond:

Thank you. I don't intend to take too long because the speakers in my session, I thought, did such a good job. Their presentations stood on their own. But, we had a lunch session the other day and Dr. Green said that he would like to have some kind of an overall statement in layman's language on what went on in the Sessions. Now, this is kind of tough because the original premise of the Symposium was to address the technical and aerodynamic aspects of the job and now all of a sudden he wants me to turn around and express an integral sign in yummy terms. Well, I'm not sure I can do this too well, but I'm going to have a go at it. I'm going to try to summarize the main points of what the three speakers did in my Session and then I am going to give a couple of research problems that I asked each one to write down for me, some with a little background and some without. For example, John Spillman only got a half-hour notice of what I wanted there, whereas Bernard (*Panneton*) had a week to figure it out. So what I'm going to do to John (*Spillman*), is not quite fair but I am going to do it to him anyway.

David Kristmanson was asked to define the drop spectra in terms of mathematics, and I wanted to do this to have a specific definition of all the good characteristic diameters of the spray, knowing full well that the rest of the talks that came were going to deal with a lot of the technical terminology of a spray. And I asked him to present atomization data from practical atomizers so that we could understand what span we are really dealing with. And he did that and he did that very well. He expressed something, which is a hobby horse that I've ridden for a long time, the interpolation functions or extrapolation functions that we use for the spray spectra, there is nothing magic about them. If they fit the data, use them. If they don't fit the data, don't use them. And he said that with great clarity. There is no magic Rossin-Ramler. If you are in coal dust, Rossin-Ramler is the one to use. If you are in a carburetor spray, it looks like the Nukiyama function is the one to use. But whichever one fits that data, that is the one to use because you are going to try to extrapolate outside your measured range and interpolate within your measured points to determine things about the spectrum. The other interesting part that David (*Kristmanson*) had was that if you knew one parameter of the spray, then you could make all kinds of statements about other parameters of the spray from that one measurement. But I got a little more out of David (*Kristmanson*) than that. I got an identification of a problem with one of the laser probes which I was unaware of and there is an area for more effort. I also got a statement on the desired drop size spectrum for spruce budworm control and a number per unit area. Now these are two important parameters which I think David (*Kristmanson*) addressed.

I'm going to do this in reverse order. I'm going to talk a little bit about John Spillman's piece next, simply because his wasn't that technical but he came again to exactly the same point at the end. He was asked to discuss improvements required in spray droplets using the results of the previous speakers and his scope was left entirely open. He used two sets of experiments to home in on a desired drop size for spruce budworm control and then he assessed the ability of some atomizers to do this job. And he noted a deficiency in the present design for rotary atomizers. He was very, very clear that you had to have a non-volatile fluid and he knew the flow rate he wanted, and he knew the drop size spectrum that he wanted. David (*Kristmanson*) and John (*Spillman*) had slight discrepancies in the upper drop size area and I don't know if that is significant or not. That's a point for discussion. But they agreed in the lower drop size end. The thing that I found most interesting, before I get to Bernard's (*Panneton*) work, was the fact that with those two gentlemen, this is the first spray meeting that I've been at where there was a basic agreement in what they wanted in terms of drop size at the target, concentration and number per unit area. In my naivety, maybe we can put the drop size spectrum to bed for spruce budworm. Those two gentlemen said from two different points of view what they think we need.

Now the most technical of the papers in the session was given by Bernard Panneton because I asked him to do that. I asked him to introduce the effects of fluid parameters on atomization from a theoretical atomization point of view where we had theoretical methods to describe how the fluid parameters entered the atomization process. And he did that with the jet and with the sheet. He related how fluid properties enter into the analysis through the Weber Number and Reynolds Number. Now, everytime you think Weber, you think surface tension. Everytime you think Reynolds, you think viscosity. This is how the physical parameters always group together. So in this way, I thought we could get to the physics of atomization, bring out how those processes work and how the fluid mechanical properties enter into that process.

Now, the stability analysis then leads to an idealized prediction in your drop size so we could get to the fluid mechanical properties affecting drop size. Now, with that said, if that's enough, I don't know, the fluid mechanical instability is perhaps more difficult to put in layman's terms. Maybe I haven't, but the idea is that we just allow a small perturbation to grow on the fluid on the free surface of the fluid and watch it grow. If it grows, the fluid is said to be unstable. If it doesn't, the fluid is stable. Another hobby horse I ride is that we always make droplets as a result of instability processes so my concept of how the fluid parameters enter is through the instability analysis.

With regard to research gaps and priority areas for future research, I asked each of the speakers in my Session to identify the top two priorities relative to the specific areas they covered in their addresses.

John Spillman's priority areas were:

1. We have to understand atomization processes well enough to design and develop practical atomizers when given the required droplet size range in field use with the desired formulation.

2. We must understand the dispersal of sprays sufficiently well as to be able to account for the destination of 100% of that emitted.

That's the mass accountancy problem. Can we account for 100% of the mass and we have to understand the dispersal, understand the physics of the transport in order to achieve that goal. John (*Spillman*) didn't have time to give any amplifying paragraph whereas the other speakers did.

Dave Kristmanson's priorities were:

3. Atomizers that give more closely controlled drop size ranges are required.

For the most effective use of pesticides, a relatively narrow range of droplet sizes is normally required. Atomizers currently used give a wider range than is desirable, and in the case of atomizers used to spray coniferous forests, give too many large drops. There is room for improvement in the "tunability" of atomizers and in control of the width of the size distributions.

4. Droplet size measurement methods used need further refinement.

Laser spectrometers have greatly advanced the state-of-the-art in measurement of droplet spectra. These devices were designed for use in cloud physics work and are not in some respects well adapted to the requirements of atomization research. Continued development of these devices would be helpful.

And might I add from my own (*Drummond*) point of view, in that regard, that the software that goes with these devices probably needs as much work as the physics of detecting the particles. The calibration of those devices is not really very straight-forward and David (*Kristmanson*) has a good point there. The calibration of the PMS probes was the subject of a series of work-shops within the cloud physics community in the last few years and, currently, within our airplanes and the ones of the Boulder Colorado people in the United States, we are always intercomparing our own results and we find that there is quite a large variation from one airplane to another. We are never sure if it's the software, the actual detection of the drop, or if it's the airflow around the airplane distorting what goes on. So it's wide open from this point of view too.

Bernard Panneton identified the following research needs:

5. Atomization of non-Newtonian fluids.

Research in this area is needed in order for advances in understanding of the atomization of complex fluids to take place. More and more fluids of practical interest are exhibiting fluid properties that do not fit into the framework of classical fluid mechanics. For non-Newtonian fluids, a linear stability analysis has been accomplished for both jets and sheets. But atomization takes the fluid into large deformations, a non-linear process. The linear analysis requires experimental verification and then the jump to the largely unknown theory for non-linear phenomena must be taken.

In parallel, an experimental program should be undertaken. The simplest problem of one nozzle and one fluid should be the starting point. With a good measure of apparent viscosity at all the necessary shear rates, drop spectra measurements would be made.

6. Droplet coalescence needs research.

The drop spectrum is not a constant as it leaves the nozzles and is in fact dynamic. It depends where you take the measurement what answer you get. Coalescence is a process that changes the drop size distribution that you can measure.

Those six problems were brought forward by the three speakers in Session II and I think there is probably a career in two of them and great advances can be made in another two of them. I think if I say anything more I'll paraphrase my authors which is very dangerous.

Chairman:

Thanks very much Al (*Drummond*). Any comments from the floor?

Steve Parkin:

I couldn't agree more with the suggestion on non-Newtonian fluids. In fact it was extremely well put down. I thought it was an ideal suggestion. The second suggestion on coalescence I think obviously is worthy of looking at. But I would just like to point out that in our experience, it doesn't appear to be a good problem in that we were interested in positioning nozzles as close as possible on a boom in order to get the maximum output with the shortest length of boom. We observed in a wind tunnel the droplet spectrum behind those nozzles to see whether there was any difference as we moved them closer and closer together. Even with flat fan nozzles positioned very close to each other we didn't get any droplet coalescence between the fans and so I would hazard a guess that, in fact, it is not a severe problem in terms of the atomization process as such. And certainly in the far field, once you get into the aircraft wake, in that area, I consider the spacing to be so far apart that it wouldn't really be of that much interest. Although I'm not trying to put a downer on it, I wouldn't put as much emphasis on it as perhaps the author did.

Al Drummond:

Yes, you are right. In the flow field behind the airplane, I couldn't agree more that coalescence will not be a problem because of the drop sizes and their dynamics. However, the context of that particular recommendation comes from the mono-disperse drop generator point of view which can be used to calibrate other devices or to be a mono-disperse drop generator for research purposes. Mono-disperse drop generators can give you, actually, quite a wide distribution unless you are quite careful. And in this context, Bernard (*Panneton*) had to work very hard to make sure that the device that he designed beat the coalescence problem. There are ways to do it, but it still needs some work on how to do that. From hanging one of those devices on the back of an airplane and expecting coalescence to be a problem I couldn't agree more, Steve (*Parkin*), but that's not the area. The area is in the research and in the laboratory scale of a mono-disperse drop generator.

Jules Picot:

I just want to share some opinions of mine with Al (*Drummond*) and George (*Green*) and everyone else here. Of the six, there is one that is critical. That is development of controlled drop size tunability. In other words, improved tunability of atomizers. There is enough expertise around in all the other five to allow us to make considerable strides in that one and I think that is the key one.

Alam Sundaram:

Al (*Drummond*), I have to commend you on the aspects that you have touched upon and I agree 100% with you in all the areas that you mentioned. Liquid atomization has been introduced very well by Bernard (*Panneton*) and I think it is very appropriate that you had him on that session. From the theoretical standpoint, he described that by optimizing liquid properties, you could minimize the satellite droplets right at the very beginning at the nozzle tip and that has far reaching connotations. It is very important for minimizing drift or in other words, droplet transport off the target. And it also has good connotations for maximizing deposit and insecticidal activity. So I think non-Newtonian fluids appear to have great potential, and therefore, research in those areas is very much needed.

I would like to touch upon the droplet coalescence and I'm so glad you mentioned that. Droplet coalescence can be dramatically observed with different types of adjuvants. If you use a surfactant, anionic, cationic, nonionic, polymeric and anti-drift or drift retardant chemicals or humectants you will find that adjuvants have a significant effect on droplet coalescence. Oil droplets, especially those I have used like Cyclosol or ID585, do not pose a lot of coalescence problems but, as you pointed out, more and more complex formulations are being introduced so we cannot ignore that aspects of droplet coalescence in our research.

Al Drummond:

Thank you.

Wes Yates:

I had a comment with regard to the physical properties affecting droplet size and I think, certainly, I agree with Alam (*Sundaram*) there that a great deal more needs to be looked at — what variables, physical properties, can do to affect uniformity and that of the droplet size that is produced. We have been involved a little bit in evaluating surface tension and the role that surface tension plays in the atomization process. One complication with surface tension is when you look at real formulations. We're working with surfactants and the static surface tension that you might measure with a surfactant in there is entirely different from the dynamic surface tension. I don't think that has been addressed and certainly is something that needs to be investigated if you are going to utilize some of the information on atomization and try to compare back to the formulations that we're using in the field.

Al Drummond:

I'm going to pass that one to Bernard (*Panneton*). Do you have any comments on that?

Bernard Panneton:

I have first to say that there are very little data on dynamic surface tension, how the surface tension changes in time after the formation of the free surface and, well, the only good data that I have seen is some of your work with a chap by the name of Hack. Looking at the time scale for the change in dynamic surface tension and comparing it to the time scale for break-up of a fluid in an extremely dynamic situation, as it is in aircraft spraying, I am not sure, maybe you could expand on that, if it is a relevant concept. In other words, the first look to me and I didn't spend much time on that, but the time scale of change in surface tension is longer than the time scale of drop break-up from the fluid and therefore that concept might not be as relevant as we could think. I'd like you to comment on that please.

Wes Yates:

Yes, just to answer that, that's the reason I was bringing it up. I don't know too much about it myself. I think that's an area where we need to have more information.

Al Drummond:

Thank you.

Alam Sundaram:

I support Wesley Yates in that the literature information on the techniques and experimentation available for measuring dynamic surface tension is inadequate. We would really like experts to undertake how, or at least to think about how to improve the techniques and experimentation. It is extremely difficult if not impossible so far with the present techniques, but the theory behind it tells us it shouldn't be that difficult, so, I think that if theoreticians can help us it would be useful.

Al Drummond:

Rarely have I ever tried to measure anything, but once I tried to measure surface tension and we bought this fancy ring balance where the ring is pulled out of the surface and they said to get the ring chemically clean. Well this seemed to me to be a very good idea and they said to burn it off. Well, we didn't have any bunsen burners in our engineering laboratory but we sure had a good welder and I got it back in an elliptical form with pieces missing. So those are the practical problems of measuring surface tension. To me, it's finding a good welder.

Marie-Claude Lambert:

Did you do before some trials with an open nozzle near the cabin but closed nozzle at the tip to decrease the effect of the loss of the small droplets as drift.

Al Drummond:

We had a full span boom with nozzles at the wing tip and near the center. The spray should be emitted inboard to reduce the effect of the vortex.

Al Lo:

I do not know anything about atomization and correlation of the drop size but I would like to make a comment on it. I come from the field of aerospace engineering and, if I remember my old field correctly, the atomization of a liquid propellant has been extensively studied in liquid-fuelled rocket engines, in the combustion chamber, and I wonder if anybody here has done any literature survey in that area. If the research has been done then we don't need to re-invent the wheel again, here. I think it is well documented in a far-advanced field in the application of liquid-fuelled rocket engines.

Al Drummond:

The rocket engine atomization occurs at a very high temperature and the types of fluids are restricted only to two. The formulations we are discussing here have a wider range of fluid properties but a much more restricted field of pressure and temperature. Carburation work is pertinent to spraying but the rocket stuff, I think, it's a little too high temperature. Chemical reactions dominate that process rather than getting the spray to be atomized nicely, uniformly, then transported evenly in a slow manner. Those guys want their specific impulse in a micro-second and are unhappy if they get in 1.1.

John Maybank:

I was going to comment on this matter of the drop size that we do finally seem to be homing in on. In some particular situations, maybe only in insecticides, although there are indications with herbicides too, we seem to be prepared now to state a narrower size range than we've commonly gotten, and I think there's an implication in this that could be very interesting to the whole development of new atomizers. Up till now we've adopted the attitude that any size range will do, and nozzle systems and atomizers for ground rigs and for aircraft have been developed in parallel. It's been long recognized of course that the vehicle, the fast moving vehicle, the aircraft, will modify the size output but as long as nobody knew what size you wanted it didn't really matter. I think we are now going to see those developments diverge, necessarily so, because for ground rig operation, of course, the vehicle speed plays pretty well a negligible role in altering the size distribution. In the aircraft it is very significant. You are no longer going to be able to, I think, say well let's work with ground rigs, we'll try the thing on an aircraft, or vice versa, which has in many cases happened. So I think we are going to see now in the development of new disseminating devices, the essential, inevitable divergence of the ground rig nozzle system from the aircraft nozzle system.

Al Drummond:

Thank you, John (*Maybank*).

Chairman:

Any other comments, questions, input, for Session II?

Al Drummond:

Could I have the last one then?

Chairman:

You certainly can Al (*Drummond*).

Al Drummond:

I'd like to re-emphasize, carry on what John (*Maybank*) was saying, the one unifying experience I've had in this whole Symposium is learning that 55 to 10 microns is the best and even though Bernard (*Panneton*) says viscosity inhibits the production of droplets in that area, that is the droplet size range we should be striving for.

Chairman:

Thanks Al (*Drummond*). Thank you all.

The next session was Spray Cloud Behaviour, Session III with Michel Pelletier as Session Chairman, Michel.

Michel Pelletier:

This will be a brief summary of Session III. This session dealt with Spray Cloud Behaviour. Four distinguished guest speakers presented different aspects of that topic to us. We saw the vortex effects on droplet motion, vortex stability, factors affecting movement of spray droplets above a forest canopy, and finally canopy penetration and impaction of large and small droplets.

It seems to be easy to produce droplets in a broad spectrum and also probably in a narrower spectrum. But probably not so easy to get all those droplets where we want them. In fact, aerial application of pesticides can be condensed to one big question: What is the best droplet spectrum to achieve the best efficacy using the right aircraft, right nozzle, right formulation and right weather conditions without being harmful to the environment? With regards to the presentations made in Session III, we should be able to point out research areas that should lead us to better aerial spraying for forest management. It seems that canopy penetration and impaction are quite well known for large and small droplets. We can, when droplets are reaching the forest canopy, describe mathematically their movements and their impaction efficiency with regards to the target and weather conditions. The main problem seems to be to get the right droplet size to ensure the best efficacy without causing any harm to the environment and to people. In fact, for small and also big droplets, measurements of spray pattern deposit within the canopy in relation with pest distribution and different weather conditions, may lead to better pesticide use strategies if we can gather more information on those subjects. Another conclusion that we can draw is that we need to develop a more sophisticated nozzle, like mono-disperse spray application systems, and I think that this is a must.

Our second speaker in Session III, Dr. Parkin, gave us a portrait of factors that can affect movement of the spray droplets above a forest canopy. He showed that movement of droplets is a rather complex process and that it is even more complex in forestry due to the release altitude and the topography. Two aspects of droplet movement should be investigated to complement what we already know: These are the evaporation of multi-component pesticide formulations and meteorological information in complex terrain with information such as spatial and temporal variation of turbulence.

Our first speaker of that session, Dr. Drummond, showed us that the vortex can greatly affect the distribution of droplets over a forest canopy and that location of nozzle and droplet size are also important in final droplet recovery. We saw also in a short film that a vortex is not something that is very stable floating gently in the air. What we saw, in fact, is something that is very dynamic, so dynamic that we do not know how it can affect spray cloud distribution. I may add that over the past two years, in Quebec, we did some experiments on vortices using smoke grenades to visualize movement of the air mass behind five types of aircraft. Our results are similar to those that Dr. Drummond described and it brought some changes to our operations.

Finally to conclude, I can say that we know a lot about spray cloud behaviour but, to really improve aerial spraying operations, we should, we must, do more research and development on different subjects and to summarize, I have six subjects:

1. To know spray pattern deposit in relation to pest distribution and weather conditions.
2. Development of mono-disperse spray application systems for both large and small droplets.
3. Modelling of evaporation of multi-component pesticide formulations.
4. To obtain more information on meteorological conditions in complex terrain, particularly in relation to spatial and temporal variations in turbulence.
5. To develop specifications for nozzle locations on all types of spray aircraft in relation to droplet size and aircraft vortex.

and finally, but not the least,

6. To understand vortex core bursting and its effect on droplet distribution over a forest canopy.

Thank you.

Chairman:

Thanks Michel (*Pelletier*). The floor is now open to questions or comments.

Charles Wiesner:

I wonder whether perhaps the panel would care to comment on what I see as a strange approach, perhaps a confused approach, to the question of the vortex. I listened to Marie Claude's (*Lambert*) questions and to Michel's, (*Pelletier*) comments and it makes it sound as if the vortex is a bad thing. And then I listen to Jules Picot and I get the impression that the vortex is a good thing. And I wonder whether, maybe, we should get straight whether we're spraying agricultural fields, whether we're spraying wheat, or whether we are spraying a forest.

Michel Pelletier:

Probably you misunderstand me. The vortex is a good thing for an aircraft and for spraying but we have to know how it is moving in the air and we should know how to use it to provide a better deposit where we want to have it. The experiment we did in Quebec took pictures of vortices from five types of aircraft. We came to the conclusion that the spray altitute for a Pawnee and for Bullthrushes should be up to 20 meters over the forest canopy and that the extreme outboard nozzle should not be at more than 65% of the wing length to avoid drift from the wing tip. The vortex is there and we should know more about it to use it in a better way.

Jack Barry:

On that line I think as we use these models, like AGDISP and the Picot model, and the other models that have the vortex code in them, we are going to understand the effects of the vortex and how to use it to our advantage. I am personally of the opinion that the vortex can be a good thing but not always a good thing. It's like all the rest of this application. We can't make a general statement about anything. We have to look at the site-specific situation. We are just starting to use the models and perhaps two or three years from now, this will be a very routine question, maybe ten years, but somewhere down the line I think this question will be answered.

Bob Mickle:

In light of the fact, as I understand it, that the recommendations are for flying in higher winds, more turbulent situations, is the vortex really all that important in as much that, again, as I understand it, the lifetime of it might be very short?

Jules Picot:

I don't want to make a snide remark. What you need is a more important vortex. In French "importante" means greater, more momentum in it.

Bob Mickle:

Translating into life times, what does that mean? For instance, with the work that you did on the TBM, what were the characteristic life times of those vortices?

Jules Picot:

(Response from Jules Picot was inaudible from the tapes.)

Lorne Elias:

Bob *(Mickle)*, I don't know if I got the impression that anybody is suggesting that we only spray in winds and turbulent conditions. From my point of view, I found that you can spray in fairly calm conditions under high humidity and in those cases, I would say the vortex is very important.

Chairman:

Any other questions or comments? If not we will move to Session IV, Spray Cloud Measurement and Assessment with Jack Barry.

Jack Barry:

I'll summarize the three papers and then after the summary, I will give a list of recommendations on factors to consider.

The first paper was Wes Yates on Laboratory Evaluation of Emission Systems. He discussed the recent introduction of laser measuring devices having revolutionized drop size measurement both in the laboratory and to a limited extent in the field with the laser system capable of being mounted on an aircraft. Capabilities exist to measure drops from 1.1 to 2046 microns using a combination of laser systems. On top of that, the software is available to put the data from these three probes together and give a complete spectrum. And that is a very recent development in the last few months at U.C. Davis, and perhaps other places, but we know that it has been done there. There are some important factors to consider particularly dealing with quality control of the data. Some of the factors would be an experienced professional to select, to operate, and to calibrate the equipment and analyze the data. It's complicated.

Number 2 is to use some standardized procedure and we understand that ASTM has taken this on to standardize procedures using the lasers in wind tunnels. So that problem that we all recognize is being worked on and Wes Yates reported the great variation from one laboratory to another. Drop spectrum measurements are essential to the models which were discussed. The models, obviously, can't evaporate or disperse a drop unless it knows what that drop is in size and frequency. So, to the modellers, this technology is very critical.

The next paper was by Martin Houle entitled Quantification of Spray Cloud Materials Within and Downwind of Research Areas. He emphasized that careful consideration must be given to selecting an appropriate sampler for a particular project. Now that seems like a rather trite statement but it is a very important statement and one of which all of us are probably somewhat guilty in not selecting the right equipment. And along that line, we probably can't select the right equipment unless we pretest it in the field before we use it. Even if it is an old standby sampler, we may be looking at a new tank mix or a new way to handle the sampler in the field, a new way to assay it or maybe all proven ways. But until you walk yourself through that procedure you probably are going to have some problems that you are not aware of. Data requirements, logistics or costs are other major factors in considering that particular sampler or samplers for a project.

We all recognize that the nature of field testing necessitates simplicity and reliability. We all have probably had experience in the field where we've gotten too sophisticated and we've lost the ball game because of that. And again we do know that each sampler has its capabilities and limitations. As an example we hear that the Kromekote card — a lot of people say it is no good — well it is good for a certain range of drops for certain conditions. So, that is just an example that each sampler has its own range. And again, this problem of standardization and calibration came up in this area. We must be able to calibrate our equipment, particularly air drawn equipment, our rotary devices, or else we can't get quantitative data out of it. And that seems to be a very fuzzy state of the art for people who are not experienced in it. And again we need caution in that area.

The last paper was by Marie-Claude Lambert on Quantification of Spray Deposit in Research and Operational Spraying Operations. She gave a strong argument for replacing the Kromekote sampler with an artificial foliage device, if the desire is to look at the relationship of what is depositing on the foliage and also to efficacy. She had obtained a high correlation of drop size between the artificial sampler and foliage sampler, in fact a very high r^2 fit. Another bit of information was that 50% of the drops she's finding are between the 27 and 48 microns, and that's droplets on natural foliage. That would be chemical and biological. The drop density seems to be between one and two drops — the optimum or the desired number of drops per needle. Obviously, or probably obviously, more would be better, but a lot of data from Marie's paper and others support the one to two drops per needle. Again, one must be cautious because that is related to the number of larvae per branch and if you have a great population as I think we've all experienced, perhaps, that number is not so fitting. A lot more work is needed in this area.

Foliage protection appears to produce a better estimate of efficacy than larval survival. That is an important statement. This is what was found in her field work, we suspect that in others' field work and there are probably several of you who could cite the same. I emphasize that because in the USFS, particularly in the West, we emphasize larval survival and with biologicals perhaps that is not the appropriate measure. Evaluation of deposit directly on foliage appears to be superior to other deposit assessment methods. And lastly aircraft tank mix application procedures should be evaluated as a package. Those factors together, because one can change the whole affair, so I think we need to be looking at things as groups instead of individually in our evaluation. I believe Marie-Claude (*Lambert*) mentioned that in our discussions.

I'll go through the recommendations. I have seven of them.

1. Adopt foliage assessment techniques as a standard measurement or indicator of a successful treatment. Encourage use of artificial foliage sampler devices.

2. Standardize field meteorological measurements and sampling procedures so that results from different trials can be compared.

3. Explore mechanisms for promoting cooperation among scientists, technology transfer, training and technical assistance. Interchange of scientists across the Canada-USA border needs to be simplified and we should explore the feasibility of having Canadian scientists cooperate with the U.S. Forest Service on western U.S. spray projects.

I would also like to propose that we explore some mechanism to get some of the eastern folks from Canada out to one of our western projects. Take a look at our unique problems that we feel are very very unique as far as getting small drops to the target. And we need all the help we can get. It's not clear to me how we would get you out there but we certainly ought to talk about it.

4. PMS System operators should cooperate with ASTM in developing standards. We would all benefit from a standard that people followed. And it probably won't happen unless you operators that haven't, push for that. It won't happen as fast as we would all like it to happen.

5. Support researching of methods to sample, detect, size, and analyze sample drops in the 5 to 50 micron range.

That's very difficult to do in the field. What we're hearing is that the small range is a very important drop size range. We're not seeing them in the field. We have no easy way to do it on an operational project. We have failures on operational projects and we would like to be able to pin it down as to why. If we can't see what may be giving us the effects then we'll probably never be able on any particular project to look at those less than 50 micron drops to be able to say yes that's it or that isn't, "that" being getting the material to the target.

6. Support research aimed at correlating small drop deposition with tree protection.

7. I just couldn't resist. This one is one we might call a social responsibility. I think we need to begin communicating with the public. If we've done it, do it a lot better than we have to develop their confidence in us as a scientific group. Solicit their support — and that filters into the politician and into financial support. It's become apparent now, sometimes painfully so, that ignoring the public leads to cancellation of a project or even keeps you from conducting a research project in their bailiwick. So I think that's an important thing, we have a responsibility as scientists to do the communicating and promote ourselves in the public image.

Chairman:

Thanks Jack (*Barry*). Are there any comments?

Marie-Claude Lambert:

My comment is about very small droplets. We are able to count and to analyze droplets to about 12.5 microns. Dr. Yates yesterday told me that there's some smaller droplets but I asked myself if these very small droplets have consequence, an effect, because when we see a block previously sprayed by a plane we see a green section. And if we know that small drops drift far from the block, but only on the block it's green, and further out it is dead or very bad. I want to know if there is a test to determine if very very small droplets are lethal to the insect.

Jack Barry:

I know the folks at FPMI that have really looked at a lot of problems related to that. Is there someone in the audience that would like to address that?

Chandra Nigam:

I used to be at FPMI but I am not there now. During my field experiments with EC formulations in 1985 we have found droplets entering into the budworm microhabitat especially on the webbing. They were from 5 to 15 microns and a number of dead larvae within the microhabitat were found. Then, subsequent to that, in 1986 we carried out experiments, comparative experiments in between ultra ultra low volume formulation where the concentration of insecticide in the formulation was 38% as opposed to EC, 11%. We have found a lot better efficacy of these small droplets in foliage protection as well as insect mortality. And there we have carried out the spectra because, in EC formulations, life of the droplet on the webbing was hardly two to three hours after spraying. So it was very difficult to carry out the computed spectra but in ultra low volume formulation which was used with Dowanol a spectrum can stay up to twenty-four hours and there we have carried out the spectral studies and we found that droplets from 5 to 85 microns were found but most of the droplets were from 15 to 25 microns. Now the question which I want to address here, the measurement of droplets in the webbing is very difficult. I was able to count the droplets, not in total, but some of them, because the webbing goes criss-cross and when you magnify, it becomes very difficult to measure the lower spectrum of droplets because you have to magnify so much that you can see very small portions of the webbing.

However, what we have found as we went down to 5 micron spectrum there were one or more droplets per web as compared to the higher spectrum. And that is, now after listening to so many people, that nozzles are producing lots more small droplets and if we were finding more there that was not unusual. So, what I am trying to say here is that droplets that you are finding on the needles are not telling the whole story because this webbing is a very nice receptor and interceptor of small droplets. Taking the terminal velocity into consideration, the smaller droplets near a needle go around it while with the webbing they are intercepted a lot better and, to this effect, a lot of collaborative work has been done by Kave Kristmanson and he should be saying more about its physics than I.

Dave Kristmanson:

The only thing I would say is that I kind of like the paradoxical results that you can get something like, if you have a, how does it work out, if you have a 5 micron web and a 20 micron particle you can have, getting on to a 200% collection efficiency as defined in the normal way. If you think about it, it's not quite as crazy as it seems. If this is the web you have a big particle coming. The standard definition of target efficiency is the drops that are in that strip out in front and there are some drops just touching the strip. So, droplets out here will just touch. So, you get 200% efficiency. I think that is really what Chandra (*Nigam*) is alluding to that if the small droplets can get near the webs they'll stay there. But, there is also the counter argument, that the webs shelter the flow so that a lot of the flow just goes around. So, that there is sort of an unknown shelter factor in the argument. But certainly, the small drops are there. They get through into the microhabitat. They are going to be collected with a very high efficiency compared to what they would be collected on the needles.

Chandra Nigam:

Along with that on the biological side, I will tell you, myself and Dave (*Kristmanson*) created droplets in between the range of 8 to 10 microns and I have used the microhabitat of fourth- and fifth-instar larvae and we have found 100% mortality but I don't want to say too much about it because I don't know how much overdosing we did. How many more droplets did we put on which were not related to the real aerially spray conditions? Because we are not able to yet analyze totally after aerial applications the spectrum going inside the microhabitat due to the difficulty of measuring these droplets. And that's what I want the physicists to help me with how we should go about measuing it? Use a holographic method or any other method? Thank you very much.

Jack Barry:

This is an interesting problem. Keeping it in perspective, and I did talk to Dr. Nigam at his poster, a very impressive poster, but I'd like to call attention to the fact that in the western budworm, in the Western U.S., the situation can be quite different. This year I was told that the insects came out early, had a great appetite, devoured the bud and the new foliage very rapidly and moved on to the older foliage. Tree phenology, difference in tree species, difference in elevations can really change that posture of the insect and certainly could affect how we should treat it. I think we need to keep that in mind along with the drop size.

Chandra Nigam:

I agree with you not only in your part, but here when I look at budworm in red spruce it spends most of time on old foliage, as compared to in balsam fir. Whatsoever I have said relates to balsam fir not to spruce. The spruce situation is totally different.

Jack Barry:

Are there any other comments on drop size? Obviously this is an area that we won't resolve here and it obviously tells us that it is an area where we need more pursuits.

Chairman:

I have a comment or rather a question to Chandra (*Nigam*). Chandra, in insect toxicology, don't we know enough now about budworm to know what the LD50 for a budworm at a given stage is. If so, if we know that, could you theorize and get back down to say how many droplets are required. . . .

Chandra Nigam:

Whatsoever past work we did, it was to extend the dosage to the field. So we were measuring droplets in micrograms per centimeter and correlating with the field efficacy. Now, here, what we need is impaction of small droplets on the budworm larvae and we are not able to create droplets under 15 microns. And, of real formulation, we can use isopropyl alcohol and dissolve fenitrothion into it and create droplets. But when I go into real emulsions, real ULV formulations, real Matacil formulations, the very small droplets are not created by the devices that we have. Mono-disperse generators clog up. Right now, myself and Dave (*Kristmanson*), are working on an ultrasonic atomizer. There we are able to create some droplets, again, not of real formulation but formulations dissolved into the volatile solvent and easily passing through. And we will be meeting the same problem with *B.t.* formulations. Creating droplets of smaller size will be difficult as we increase the concentration of BIU's in the formulations. Ultra ultra low volume of *B.t.* is becoming important and more effective, but we won't be knowing what type of droplets are going unless we do the laboratory toxicological study. No doubt I spent last 15 years working on — developing — LD50, LD95 values, but we have not worked in this fashion because we were looking at problems in a totally different way. To promoting what dosage we can use in the field, so, all that toxicological work is not relevant to these small droplets under field conditions that we are seeing now.

Pierre Mineau:

I'm getting a bit confused here. I think we have sort of sidestepped part of Marie-Claude's (*Lambert*) question here, which was if it is the 5-10 microns or very small droplets that impinge on the micro-habitat of the budworm and do cause the mortality, yet we know these droplets have very low general impaction efficiency, why is it that we are seeing the sort of stripping that she describes. In other words, we do not have kill outside of the direct spray path of the airplane.

Michel Pelletier:

I can comment on that. I would say that even after probably 30-35 years we don't know yet what is the best droplet spectrum to affect SBW. It is probably the same thing for many other pests or other weeds. We're spraying — we're producing droplets — we're having droplets on foliage somewhere and we're getting results. But we're certainly not having the best droplet spectrum with regard to the biology of the insects. And, I'd say that this is one of the first questions or answers we should have to initiate a good spray project. And with regards to what Marie-Claude (*Lambert*) said, in Quebec, sometimes in the Gaspé Peninsula, we saw spray blocks all green and we can see the boundary of those blocks and the forest was red just behind that green block. So we're thinking that very, very small drops, due to drift, they're not really good. If they were, all of the Gaspé Peninsula should have been green.

Jack Barry:

Ed has his hand up back there.

Ed Kettella:

I have been a quiet little dude the last couple of days but I'm not going to be quiet anymore. The question I think that Pierre Mineau asked, why the striping, can probably be answered in one word — vortex — aircraft vortex — when you get it into the trees. But to go on beyond that, this business of small droplets, I can't reiterate Dr. Nigam's results enough, in that the work that we've done in New Brunswick for the last four years, looking at spray impaction and foliage protection, we feel that the only part of the spray cloud that is doing anything is that in the less than 50 to 5 micron fraction. The development of sampling for deposit, expressions such as deposit per needle for *B.t.* efficacy, we've demonstrated clearly, first of all, that there is a clear dose-efficacy response. More droplets per needle, the better the results. But the other curious factor is that when you use more and more concentrated *B.t.'s*, in this case, you get that one droplet per needle for say, a 32 to 48 BIU product, all of a sudden you get the same efficacy down at 1/4 of a drop per needle. That tells us that, in fact, what we have developed is looking at nature's very own, very best Kromekote card for estimating deposition. But in fact, how the insect gets the correct dose to turf it in is a completely different mechanism. The work that Dr. Nigam has been doing, I think, is on the right path to quantify and qualify that particular pathway. I don't want anybody to leave this room thinking that you can go out and say, well we're going to write a prescription; we are going to have one drop per needle; because you can be fooled. There's such a wide variation in depositions but the important things is that, with increasing concentrations of material you look at, that particular estimator of deposit is the. . . . what you need for deposition all of a sudden drops quite markedly. That's all I've got to say.

John Ray:

We have observed quite a clear cut-off when we have applied fungicides with small droplets in a disease situation in the forests, so I think that if you get the right conditions, then you will get a sharp cut-off. I don't know what the conditions are.

The other thing I'd like to comment on is the last point that you raised, public relations. I think unless you can convince the general public that you are doing a good job and that spraying is necessary then discussing what sort of research you should be doing will be rather academic. We mounted a spray operation in the built-up area of Auckland some years ago. We were asked to control silkworm larvae. We sprayed a school grounds and the reserve alongside it and this was right in the center of Auckland. Our Ministry of Agriculture approached all the people who lived round this block. They explained exactly why we were doing the operation; they explained the reason for it. The reason was that the insect, if it became established, would threaten the crops, the apple crops, in New Zealand. We got a very good response from the press. We got a good response from the television. They made quite a lot of this in a favourable way. We completed the operation. The only person who was frightened was the pilot of the helicopter who did it. I've never seen anybody leave a spray site quite so quickly. The operation was shown on television and there was no response at all. It's just a question of having good PR. You must explain to the general public and get them on your side.

Michel Pelletier:

I'd just like to comment on spray deposit assessment. What Marie-Claude (*Lambert*) presented is a way to assess efficacy of a spray application. But what we are saying also is that for each product, each concentration, each situation, we will need to re-do all those experiments to check the efficacy of each product because they are having their own efficacy.

Jack Barry:

You mean to calibrate the samplers for each product.

Michel Pelletier:

No, I think that if we use balsam fir foliage, it's a natural target. We'll have to check for every product and every concentration because they all gave different answers.

Alam Sundaram:

I have an entirely different problem which has not been touched so far. That is, the uniformity of deposit over the target area. Over approximately 40 to 60 spray trials in the past 8 years, our Institute has monitored the deposit both at canopy levels and ground levels, intermediate, at all levels and assessed the deposit in terms of droplets or in terms of active ingredient and also in terms of tracer dyes. What we found was there has been no systematic pattern of variation which we can relate to either wind speed or vortex, a difference in the atomizer settings, a difference in atomizer used, a difference in aircraft used, and also difference in temperature conditions. And so, we found in quite a few trials about a third of the block gets very low deposit, both in the canopy and on the ground and the rest of the block gets high deposit. Sometimes half the block gets very low deposit, half the block gets very high deposit. We all know very well, both the regulators as well as the efficacy people, we would like to eliminate excessive deposit of insecticide over a particular area and undesirably low deposit in other areas. *(The remainder of Alam Sundaram's statement was inaudible from the tape.)*

Chairman:

If there are no other questions or comments, we will now move to Session V, Modelling of Spray Cloud Behaviour, with Dick Crabbe.

Dick Crabbe:

Well, OK, we had Session V here in connection with mathematically modelling spray cloud behaviour. We had four invited papers and a fifth which presented some assessment of the ability of these models in a different situation from that for which the model was originally designed or applied. It turns out that it's a bit of a shame that the aircraft is involved in this problem because it's probably the most difficult part of the whole spray cloud evolution to compute. Nevertheless, there have been very significant advances made and applied in the case of all models and probably the seminal work in this connection was done at ARAP by one of our speakers — Bilanin, and Teske, Llewellyn, Donaldson etc. and that particular vortex code appears in the FSCBG code as a recent addition and is now called FSCBG2, that's the paper by Bowman and Geary etc. We had a third paper, of course, on this problem of spray drift from aerial applications by Prof. Weihs and another paper, the paper presented by Prof. Picot, the PKBW paper. The PKBW uses the AGDISP or the ARAP code. The physics of the vortex wake behaviour, we believe, is fairly well established. The Weihs model has another attack at the vortex wake behaviour but again based on good physics and undoubtedly, as a result, will ultimately prove to be quite successful.

The Weihs model was developed for smooth ground, of course, and that's another problem in aerial forest spraying in the presence of the forest. It is very difficult to compute, for example, the erosion of the dominant transport mechanism in a forested environment. The dominant initial stage transport mechanism is, of course, the vortex wake of the aircraft. AGDISP has a stab at this by employing a vortex extinction parameterization. PKBW by Prof. Picot and Wallace and Kristmanson, realistically predicts vortex behaviour but down to, say, the displacement height of the forest. It's not clear at this point whether we have to take the vortex into the trees. It seems to me that, from the work that AGDISP has done, that the erosion of the circulation, the dissipation of the strength of the vortex, a loss of circulation is so pronounced that perhaps at least for a forest, we can dispense with this problem in the upper stages of the canopy. Now, the Weihs model, which was the fourth invited paper here, is being extended to rougher terrain. At the moment, its physics is good for the smooth ground, the interaction, the viscous interaction of the vortex flow field with the ground using the viscous boundary condition and the vortex rebound that results, but when applied initially, at, this is an early stage of extension of the Weihs code to a rough lower boundary, so far we see there are problems because the explicit canopy features have not been incorporated as yet. Nevertheless, I believe this model does have sufficient physics.

Now we have also the familiar FSCBG paper which, as I said, was presented as the FSCBG2 paper, including AGDISP for the vortex code, and when applied to the Program Wind deposition data, taken at various locations in the U.S., my impression is that there is little to choose at the moment between AGDISP and FSCBG2 predictions. But this may in fact arise just because of the variability are unescapably small but nevertheless present variability in the data. It might be worthwhile to point out that AGDISP has a propeller wake code and it can include helicopter aerodynamics and as long as we insist on delivering these materials to forests with lifting configurations these particular advantages are worthwhile. One thing that the AGDISP did that was very interesting, in my view, was to show that for ordinary aircraft in use and ordinary droplet spectrums, ordinary emission rates, that the largest droplet which behaved, which conformed to vortex behaviour, was about 250 microns. This is a point which has been bounced around a bit in the last three or four years because modelling exercises that did not have the advantage of a vortex code and which treated highly poly-dispersed aerial sprays were always lacking some guide to the largest droplet which had to be treated for off-target drift.

By and large, the Program Wind diffusion and deposition data were reasonably well predicted. It is interesting that the AGDISP has second order closure for turbulence to predict spread — droplet spread — about the mean trajectories in the wake. FSCBG2 uses slope Gaussian which begs the question of what mean wind speed you should use for slope Gaussian. But nevertheless, it seems to perform well. And, in addition, there's a menu-derived application for PC's which, undoubtedly, will prove to be quite useful for spray operators. AGDISP is going the same way I understand, if not already there.

The other half of this particular Session was devoted to the Dunphy Experiment and the ability of modellers to predict what we found in the Dunphy exercise. This particular study was, as has been indicated earlier by Lorne Elias, has terminated after several, perhaps five years of study in New Brunswick and was set up to determine precisely what meteorological conditions are best to suppress drift and enhance deposition. It turns out that when the PKBW and the Weihs model were applied to the Dunphy data, that neither model predicted the effect of atmospheric stability. But I can see that there were problems in even getting good predictions for the neutral case, so I don't believe that's a major drawback of either model. The PKBW model looked reasonably good in terms of deposition but there were departures from the actual deposition profile and when you consider the fact that many of the Dunphy tests — perhaps half of the ten particular trials in 1986 — did not meet budget closure, it's understandable that some of the departures, some of the discrepancies between model prediction and measurement could be due to this source and not to the deficiencies of the model. I was interested to see that the PKBW model did predict, reasonably well, the vertical time-integrated droplet concentration profile in the neutral flow at 400 m. Now, this is the only model that did so but then we are only speaking of two models, the Weihs model and the PKBW model as far as the Dunphy data is concerned and the Weihs model, of course, as I mentioned earlier, is still under development, but the physics look good at the moment.

Now, a fifth paper which we can't overlook here, was presented by Bob Mickle who spent some considerable time in applying the codes that I've alluded to, to the Dunphy data. Prior to doing that, Bob (*Mickle*) and Ray Hoff, in an illustrated sequence, demonstrated the utility of a Lidar cloud mapper and I thought that was very interesting and worthwhile part of this particular exercise in understanding spray cloud behaviour. However, the actual purpose of Bob's (*Mickle*) paper was to look at the performance of these models when applied to the Dunphy data and it is difficult to be very definitive about the comparisons. One would almost have to be a bit superficial and say, in assessing the model performances, that they all appeared to pick the peak deposition correctly but they were generally not conforming to the actual measured level of deposition. The earlier models from the U.S. had essentially the same difficulty. It seems to me that the models do have a considerable degree of utility. They may have more utility in a couple of years as we can simplify perhaps, and understand better the vortex physics and possibly implement it better in numerical models. Part of the problem I suppose in the disagreements that Mickle's paper showed between the Dunphy data and the performance of these models may in fact be attributed not only to experimental scatter, the deficiencies of the actual measurements, but possibly to required improvements in the codes.

The suggestions that I would make as a result of this overview is that it might be worthwhile to pursue the parameterization of vortex extinction in the canopy. AGDISP has some logic in the program to do this but AGDISP does not include, explicitly, canopy-foliage impaction. PKBW, on the other hand, has an explicit code for canopy-foliage impaction but it stops the vortex above the trees. It is not clear to me yet whether it is necessary to bring the vortex into the trees. If it did get into the upper reaches of the canopy, it might in fact contribute to the impaction by its own flow field. But this is a question that it is difficult to generalize and it's probably dangerous to generalize. It should be modelled. Both AGDISP and FSCBG2, as I mentioned earlier, are PC oriented, or will be, and menu driven. So, that is a good point. PKBW could be taken this way eventually.

Another point that occurs to me is that the operational spray situation is never done in winds which are truly orthogonal to the flight line. I think Dr. Elias mentioned that earlier today. We know enough now about turbulence, about the Lagrangian time scales, for, not only the vertical velocity fluctuations but the Lagrangian time scale for lateral velocity fluctuations, to determine what is the effect of the oblique line cloud and I suggest that this might be a worthwhile exercise by the modellers because it is the standard situation, apparently, rather than an infrequent situation.

None of the models predicted, or were adapted to predict drift beyond 1 km. Of course, the FSCBG2 model could do that. PKBW stopped at 400 m. The AGDISP is near-field. It incorporates the vortex physics code and second order closure but it wasn't extended to long distance. And by long range drift I mean greater than 1 km. I don't think this is important to the forest operator but it is important for health considerations. In this connection, it might be worthwhile to raise a point that hasn't been raised in this meeting so far and that is that none of the terrain over which aerial sprays are conducted can be considered really flat and ideal. The Dunphy case, for example, was maybe considered textbook flat and horizontally homogeneous, but that is just a single site of what is rather rough topography in New Brunswick and the same thing applies to many, I'm sure, to the situations in the western U.S. and in western Canada too, especially in the mountains. We should develop some way of correcting long range droplet drift using a mass-consistent wind field and the techniques to do this are computer-intensive but they are available and they ought to be included, in my view, if we are really to tie up the long range drift as well as the initial deposition of the ultra low volume droplet sprays.

Well, that concludes my assessment of Session V, the Mathematical Modelling of Spray Cloud Behaviour and I would say, overall, it was a good attempt and a useful exercise to undertake.

Chairman:

Thank you Dick (*Crabbe*). Any questions, comments?

John Spillman:

I'm afraid I woke up early this morning and thinking about this session I was still confused and I had a bit of time to make a few notes and I would like to share my thoughts with you.

First of all, I felt that the agreement between the results of the models and the experiments was unsatisfactory. Generally remembering that in many cases the down wind distances that were plotted were on a logarithmic scale. The reasons for this discrepancy, I felt, were due to, possibly could be due to, inaccurate experimental results. When you are looking at the model, the thought that struck me very strongly was that a lot of the models were being compared with experiments in a region where, on the leeside, the last part of the forest and the downwind part beyond the forest and, of course, in that region the local air flows associated at the end of the forest will in fact have a big influence on droplet behaviour and deposit. So I didn't think that that was fair comparison. I think it is important that we must compare experiments which do in fact correspond to the conditions assumed by the models. For example, we must have an experiment which gives near 100% accountability and one that is in uniform canopy as far as possible.

I felt that the model assumptions were mixed. Each of the different models had different assumptions and I felt that each had good points and each had weaknesses. But the thought that crossed my mind strongly was that we need to use those models to repeat — to repeat those models — varying only one parameter and that, in order to help perfect the models, we need to do experiments which are not necessarily concerned with the spraying against spruce budworm but are deliberately planned to help eliminate or elucidate the sort of constants that have got to go into the model. The only example I thought was really superb in that respect was the one, the experiment, that was associated with the vortex decay effect of the canopy. I feel we could do a lot more of these sorts of experiments to, in fact, isolate the particular parameters that need to go into these models. In other words, we want specific experiments to link with modelling. In this respect, I felt that the results that Dr. Drummond presented the day before were in fact, or was it that morning, were in fact equally valid and should, in fact, be included in this aspect of assessment.

The importance of other inputs into the models, I think have got to be done by these special experiments. For example, the effect of drop size in which case we obviously have got to use non-volatile formulations for that. Near monosize droplets so maybe we've got to use X-l's, or something like that, in a very low flow rate to get a fairly precise droplet range size. Incidentally, as far as evaporation is concerned — I hesitate to say this in a country that produces maple syrup — but molasses is a very good way of restricting evaporation. So that if you have to use a water-based spray, putting molasses in does help considerably. But coming back to isolating different things, the effect of volatility on the formulation, the effect of wind speed still hasn't been clearly stated. The effect of height of release, well this was mentioned, but if it's isolated, if we could keep all the other things the same, both in the model, and in some of tests, we might well be able to get a better understanding of what's going to happen.

The effect of ground viscosity and induced vortex on the modelling results: Now, I think here if we are modelling a forest canopy you have a very different situation from that if you are modelling firm ground and I felt strongly that the work Prof. Weihs reported on the ground effect, the secondary separation of the viscous layer associated with the ground, was a very important feature and must be included in modelling of that sort of scenario.

Now, the overall point I felt was that the overall comparisons of models and experiments needed to be done by people who were familiar with both the experimental and the modelling techniques. I got the impression yesterday that the individual speakers knew about their own aspect but, when asked questions, were not familiar with the other inputs, about the whole thing, and unless the whole thing is viewed as a whole, we are not going to get anywhere. We have to remember that initially, we need experiments to support and improve the models. Therefore, these need to be simple and specific. And finally, the models must be used to reduce the number of trails by modelling different scenarios and determining critical parameters as well as predicting overall results.

Jules Picot:

Thank you, Mr. Chairman, for giving me more than equal time, more than I deserve. I just wanted to clear up something that Dick (*Crabbe*) has mentioned which is not correct. The PKBW model does predict increased drift when you go from a neutral situation to a very stable situation using uniform flying height. Thank you.

Dick Crabbe:

Yes, thank you Jules (*Picot*). I didn't bring in that aspect of stability on drift because, well it didn't seem to really follow from all the papers but I agree and I am pleased to see your model does work that way.

Lorne Elias:

Can I ask something that borders on blasphemy here. Are there limitations to modelling? Are we expecting too much of models? They are highly empirical as is. To perfect them, are we going to have to introduce more empiricism or am I being too negative?

Jack Barry:

I'd like to make a brief comment along that line. I think we are expecting too much of models. I think we need to examine how we are to use models, and when we compare models to one field experiment, which is well-conducted, but rather limited and draw conclusions, I think we're skating on very thin ice. And the reason we are, obviously, is that we don't have any replication. One field test is one field test. But on top of that, making those kind of measurements in the field, is very very difficult and our models are precise. So we're trying to compare two things and I think we've got to really be cautious with that. I'm really amazed how well these models did and I think we're being a bit too critical of their capabilities.

John Spillman:

Can I just comment on that. Both the random walk and the other systems are in fact probability systems so that we can hardly say they're precise. The mathematics of them is precise, perhaps, but I mean on the random walk system you do 4000 runs and take the average.

Chairman:

Thank you ladies and gentlemen, that's all the time we can devote to this Session. I know Bud Irving is sitting up there in great anticipation. Bud, what about Session VI, Operational Considerations?

Bud Irving:

As a matter of fact George (*Green*), just the opposite, I would have thought you might go to four o'clock and let me off the hook.

Our group carried out a review of what was classed as acceptable spray weather. Basically, this boiled down, I believe, to certain aspects of stability. I don't intend to paraphrase the various items covered by the speakers or even to attempt to do a Reader's Digest condensation of them. But moving on, we also reviewed identification of acceptable spray weather. Now, I think this came out very, very well as far as experimental work, where we are doing actual research. I think that the reaction that came from the audience was, to put it bluntly, as more than one person said, "he didn't answer the question". I think that the individual was very honest from the panel when he said "we don't know the answers".

We reviewed the Biological Interface which emphasized the behaviour of the insect. There is a lot still to be learned about this and we didn't talk about the degradation of insecticides to any extent, whether they be chemical or biological, but a good part of this has been pretty well documented so that I don't think it was necessary to do this today, except to realize that when we're talking about specific insecticides that they may have different degradation rates and that there are probably things that can be done to formulations to retard their degradation. And once again I'm talking about both chemical and biological insecticides. We went on from there to the results of post-spray weather and how this may impact on whether or not we get the kind of protection that we desire.

Unfortunately, just about all of our discussion this morning referred to the use of insecticides and we have a very large segment of the audience here, that is primarily interested in herbicides. I think that it was a consensus of our group that we had, to a considerable extent, neglected part of our audience. The other thing about it was that we also, with insecticides, zeroed in on a particular insect, one that maybe has been studied more in recent years in Eastern North America. Some of the principles applicable to the spruce budworm are certainly applicable to other insects. Some of them are not.

Now, what I've been trying to pass on to you, is some of the discussion that took place at lunch hour. Remember that we were the last session and we wanted to eat and some of us were thirsty so that we tried to put together some sort of consensus over lunch. I must admit that we got really side-tracked at times and we maybe went off in some rather interesting directions that were maybe not quite in line with the intentions of this Symposium. So, instead of going any farther on this, I am going to list, with a brief description, some R&D projects that were suggested at lunch time.

1. This relates to the lack of an appropriate answer to how to identify acceptable spray weather. As I said previously, Prof. Dickison pretty well zeroed in on stability as did some other speakers on this. The suggestion that came out of this that probably could be achieved with a reasonable budget and in a reasonable time would be the proper instrumentation of an aircraft to measure temperature profiles. It was mentioned that this has been attempted in a half-hearted way over a couple of years but it had never received the attention of a researcher that it would require.

2. The second thing that came out was one that has been repeated several times here this afternoon by this panel and that is: Improved atomization devices will be required. And I want to emphasize something that wasn't said here this afternoon and that is that the improved atomization devices, if we're talking about rotary atomizers, have got to include some mechanism so as to maintain a constant RPM so that we will be getting a uniform droplet spectrum from minute to minute and over a time period. These devices, whether they be rotary atomizers or whether they be some other type, we will need them specific for both small droplets for insecticides, and for, "large" drops for herbicides. I don't think I need to emphasize that one anymore although there was a lot of discussion about it.

3. The third thing that came out was that there is a need for further, once again in quotes, "Dunphy Type" work to fill in gaps in data, some of which were identified here (and there are others) and also to confirm some of the data regarding which we have reservations about their credibility. Once again, this is a little bit parallel to where we must make sure that we can verify the models that are developed and that we don't go blindly using them and believing them.

4. Further studies regarding budworm activity in relation to weather. Here again we're zeroing in on a particular insect, but there was no doubt, in most of our minds, that Dr. Nigam has something there with regard to the droplets and that there are a lot of questions even though we've been studying the budworm for the last forty years. There are some aspects of its behaviour that we have not very carefully documented or characterized.

And then, something came out of left field. Once again, it's a little bit off the Symposium's original objective but it is:

5. Have we given enough consideration to discouraging insects from feeding rather than attempting to cause immediate mortality? Wouldn't it be much better if we could use some sort of a substance that would be socially, culturally, medically acceptable, even though we had to use copious quantities of it that would make the budworm unhappy and maybe kill him psychologically or let him starve himself to death. I don't know how practical this is and maybe somebody will shoot it down right away but there was a suggestion that there are huge sulphur deposits in Western Canada. What would sulphur do to a budworm if we were to put it on? Maybe there'll be some comments on that.

6. The other thing that came out very obviously was that the weather criteria that we had identified had been identified specifically for insecticide spraying of forests and just how applicable these criteria were for herbicides, I think would deserve some comment and consideration.

7. Number 7 was to investigate techniques for treating small areas. Now somebody said, what is a small area? I can give you any kind of a definition of it but if you want to pull something out of the air, let's talk about 50 to 100 acres or something of that nature. In the treatment of this small area how do we avoid the so-called edge effects? This leads right into the characterization of the vortices from rotary wing aircraft and their deposit patterns. We in New Brunswick have had to treat some of these small areas. As a matter of fact we've had to treat a lot of these small areas. Contrary to the experience that has been mentioned in Quebec, we do not see a clear cut-off. I have flown over many of them and I can't tell the difference between the sprayed and the unsprayed areas. I challenge some other people to identify them. Maybe we have the wrong technique. But this is an extremely important problem as far as giving protection to small, high-value areas as it certainly has not been solved either theoretically or in practice in New Brunswick.

And here is an old one I'd like to throw back at you and that is the development of a navigation system for both fixed wing and helicopters so that we can make use of the vortices, so that we can fly a track that is uniform and so that we won't get windrowing and so that we won't have to rely entirely on our drift as we do now. I think I'll quit there, Mr. Chairman, and possibly there'll be a comment or two.

Chairman:

I'm sure there should.

Ken Scheske:

Bud (*Irving*), a couple of things I want to bring up. Number one, with the weather side of it and the gentlemen who were talking about on site weather. The observation I have to make is that all those weather observations they were making were on-ground observations and not in the air observations. From practical experience, I have found before you take off in the morning as an operator, you can get information on humidity, barometric pressure and temperature very readily, and also the wind in the location you are taking off from. However, let's say in regards to forestry, where you are taking off from and where you are going to be working that morning are two different things. They may be as far as 30 or 40 miles away. What we have found is that the most invaluable tool in our operations is an on-board smoker on the aircraft. Has anyone in the research community looked into using the information they get on weather from their ground equipment and also using the smoker on board an aircraft before they go spraying? In other words, once I get to the spray block, early in the morning, let's say, with the smoker I'll run a line of smoke over the block. First of all I'll be able to tell if the air is stable or unstable by the action of the smoke. Either the smoke is going to hang there and do nothing or it's going to go down into the trees or it's going to move off to the side. So I've also got my wind direction and the stability and I'm getting conditions that are right on-site, not at the airport, or at a tower 20 miles away or 10 miles away. The other thing, if you are working in a forest-type condition, you can have people go out there, as they did 20 years ago, and build a smudge for you a couple of hours before you are going to spray, with old tires or something, and that smudge will still be burning when the aircraft gets to the site and that will also give you a very good indication on the stability of the air in that location. Has anybody looked into using the experiments that they are doing right now in conjunction with on-board aircraft experiments and see how the two correlate with each other?

That's the first thing I had and the other one I had was just an observation that, ... I bought a business from a gentleman about ten years ago, an aerial application business, and when I bought it from him, he was just in the business of up-grading from small aircraft to larger aircraft. His major complaint was that, through the years, all the regulators and the chemical manufacturers were trying to get increased volumes to be placed on the target areas, and, therefore, we needed bigger aircraft. What I'm hearing here today is, or through the last couple of days, is that we are showing that we need smaller micron sizes to do a better job on the targets and lower volumes. So, are we not going back to a position where the sprayers maybe were 20 or 30 years ago, where they were using very small aircraft and very small volumes on their blocks and is that not the direction we want to be going into? Now if we are, we also eliminate another problem. With bigger aircraft we have very big vortices. When you have small aircraft with high wings you have very small vortices because of your weight ratio. Are people looking into this and also the information we're getting here on the lower volumes, smaller micron sizes, is this information going to be getting to the regulators and to the chemical manufacturers?

Bud Irving:

I think we probably have three or more distinct questions in this. I don't know whether there is anybody in the room that has done any specific comparisons with using a smoker on an aircraft. I see a hand go up. Norm (*Akesson*), would you speak to that please?

Norm Akesson:

California regulations require a great many things in regard to application. One of them is to not apply certain types of restricted materials during stable air conditions. In order to evaluate what was stable air, we ran through the same discussion that we did this morning. Who's going to pay for the equipment? What sort of equipment are you going to have? How high are you going to measure it and all the rest of it. We ended up, like the gentleman who just raised the question here, with the rather pragmatic sort of approach of putting, first there was a lot of tires burned on the ground and of course the meteorologists will tell you very quickly, that may or may not tell you what you want to know. There's a heat effect from that plume. Then, the follow-up on that was the use of oil injected in the exhaust of the plane to lay down a smoke pattern to see what was going to happen to it. This was accepted then by the California regulatory people with one exception. The air pollution people didn't like all the dirty smoke around the area. And so there was a kick-back on that. But the air pollution people and the agricultural people got together and, I believe, most of the counties have accepted it in the U.S. at the present time. You do use smoke to determine when you're working with a tricky material under tricky conditions, use the smoke.

Now, one of our extension people thought this was a great idea, he was a rocket man and he loved these pictures of the smokes. I can remember him bringing pictures of the rockets going off into space and what not and he thought there ought to be a way to correlate the smoke behaviour, when released, with particular patterns of weather. So he went through this and he produced a big array of slides and a marvelous sort of a picture of all of this and for us, who were technically willing to go along this maneuver and sort of follow through and say yes, we recognize what is going on, well and good. But when we took it to the airplane operators why, they weren't very enthused about this. It was too complicated for them to use. Now, that doesn't mean to say that a little one page sheet with different smoke characteristics wouldn't be good to pass out. But when we tried to get down to say, this is a two degree temperature difference plus or minus; this is with five miles an hour wind; this is with one mile an hour wind; we started finding that these things start to lap over one another. And so it was not that clear and straightforward and what the airplane operators were saying is more or less where it ended up. I don't say that this couldn't be carried further but that was the end result. Thank you.

Bud Irving:

I don't know whether anybody else wants to comment on airborne smoke generators. We have had some small experience with them, not particularly satisfactory. I wouldn't say that it was scientifically evaluated, I'd rather pass on it. I don't know that we've answered that question satisfactorily or not. Probably not. I'd like to go on to the next part of your question though, and that has to do with the elimination or the reduction of vortices. I believe that we want to go — the feeling of the New Brunswick Spray Efficacy Research Group is — that we want to go just in the opposite direction, and develop as strong a set of vortices as possible. Rather than answering this myself, could I ask Dr. Picot to make a comment or two on this one? Then it leads directly into the size and type of aircraft that would be most desirable.

Jules Picot:

Now I know I'm getting more than my share of the air time. The Dunphy experiments showed, and I'm talking about the experimental results, that the heavier aircraft has an edge over the lighter aircraft in giving a stronger deposit. We get a better deposit — we get more deposit. From this and from the modelling work that we have done, it is clear to us that heavy aircraft will produce a vortex which has more momentum in it if you fly it at a reasonably slow speed, at a speed which is still operational, still maneuverable. The other thing that has appeared out of the Dunphy experiments is that the heavier aircraft is easier to fly in a turbulent situation and that the pilot, therefore, doesn't have quite the reticence in staying down at the height that he can manage quite well when its very stable. So, OK, there are two effects. There's what I think you might call an indirect effect, what I might call an indirect effect, but which the pilot would call a direct effect. It's easier to fly the thing at a low altitude because it is heavier. Secondly, it has a stronger downward vortex because it is heavier. Thank you.

Bud Irving:

Thank you Jules (*Picot*), I would like to just lead on with a little bit of thinking and then we'll get to you John (*Spillman*). Our thinking in New Brunswick for insecticide spraying of budworm has been that we would like to go to a slightly larger, multi-engined type aircraft which would have a two pilot or two person capability so that we could have our navigation system on board whether it be an INS system or whether it be an improved LORAN C and that the aircraft would not only have the capability of spraying at a reasonably slow speed with a heavy vortex but also would have the capability of ferrying long distances with a very concentrated insecticide and that, if the turbulence were permissible, that we could spray for longer periods under what are termed to be more desirable weather conditions. I think, John (*Spillman*) you have a comment on this.

John Spillman:

I wanted to talk a little bit about aircraft vortices. We want strong vortices in order to create a strong downwash between them. That downwash will carry droplets, particularly small droplets, down with it. We do not want to put those small droplets into the vortex right at the beginning when the vortices are high above the canopy, because they will then effectively be released, or some of them will be released, high up and increase drift. It is possible to increase the strength of the vortex of an aircraft very considerably by simply lowering the flaps. If you lower the flaps of an aircraft, it is possible to choose a speed at which to fly at where the effective lift comes all from the flapped region of the wing in which case, the outer part of the wing do not lift, have no vortices on it, and you will get very strong vortices off the ends of the flaps. Of course, bearing in mind what I said earlier, it means that the spanwise extent of the spray will have to be further reduced. Otherwise under that condition, you will have a lot of the spray going into the vortices, the strong vortices, early on. The aircraft would almost certainly be flying more slowly. It would have a smaller swath width if you are thinking of placement spray type systems. But of course, if you are thinking of using the cross wind approach, then you'll get the spray down close to the canopy quickly and allow the wind to carry it through.

Norm Akesson:

That bothers me a bit, because, in working with pilots, and working with operators, the smaller planes generally are willing to fly closer to the ground and get this type of activity and yet, Jules (*Picot*) is saying that the larger planes are. Are you proposing to fly a multi-engined plane ten feet off the tops of the trees? I'm just a little bit confused about this. How can you rationalize this because the effect of the vortex is also affected by the distance you are from the ground or from the tops of the trees. How do you rationalize this?

Jules Picot:

I don't know. I don't think anyone would be flying ten feet above the trees.

Norm Akesson:

I'm sorry, just take any height you want to take and take the different sizes of planes. What's the effect of your large plane? How close can a large plane fly to the ground? How close would they fly a C130 or let's say a four-engined plane to the ground? How close can you fly to the ground without hitting the trees?

Bud Irving:

Could we use the microphones please? I think everybody would like to hear this exchange.

Jules Picot:

We've been measuring TBM flying heights for a number of years. We had one pilot who systematically would fly the darn thing at between 29½ meters and 30½ meters above ground when the trees were about, well, the highest ones were about, let's say, 20 meters. Regularly, I think, you can get, well, since that time, we've had people flying, some other pilots flying, a TBM at about 30 meters. It seems as though the Ag Truck pilots are quite uncomfortable flying at 30 meters over the same forests.

Norm Akesson:

Well, then, how do you account for the Ag people flying within ten feet of the ground.

Jules Picot:

We are looking at a forest where there is a great disparity in tree height. We don't have a uniform stand height. You have the occasional dry pine tree sticking up 15 meters above the rest. And you have, you know, some mixed growth.

Norm Akesson:

Essentially, Jules (*Picot*), what I'm still concerned about is that four-engined plane flying close enough to the ground to produce any real effect of its downwash. Is that a possibility? Can he fly close enough to the tops of the trees to really get a boost from the wash that you get from a big plane.

Jules Picot:

Well, when you mentioned four-engined planes. That is an escalation over what we mentioned a minute ago. But I think there's some experience here in the room or there was earlier on. Conair Aviation are the people who are experts in flying four-engined planes very close to water surfaces and ground surfaces but where there are no trees. All I can say is that I've seen some vortex patterns coming from these DC6's with, I guess, full flaps and you'd swear that the stuff is going straight down. So, from those limited observations, you know, I think that the argument is a sound one.

Bud Irving:

I don't know where we're going to end up with this. Yes, Miss Haggis.

Margaret Haggis:

I came into the budworm program in the 70's through aircraft work, to try to follow what was happening to the moths themselves. We were working on cotton pests in Sudan at that time, and to do this, we had a spray plane, a Pilatus Turbo Porter, specially equipped with navigation aids and a whole lot of other things through the series of trials to measure the atmosphere as closely as possible to see how it was affecting moth movement. We were using Doppler at that time. It was originally hoped it could be used for track guidance and it proved not to be quite accurate enough for laying down spray lines, but it was very good for finding our way around in the desert. I suggest it would be adequate for finding the way to a forest spray site, equally. The advantage of Doppler was that we were able, by measuring the aircraft's movement relative to the ground, and the aircraft's movement relative to the air, from standard instruments, we could get the wind. We were also looking at the temperature and humidity and, I have to admit that we really went back to Mickey Mouse systems for this. Our strut psychrometer came from the Met. Office museum. The reason we used this was that it was accurately calibrated and we had access to nothing else that was. It was quite possible to have an observer in the Porter, which of course was an active spray plane between our research flights, and I was able to take measurements from all the instruments to work out the winds and the temperature and humidity in flight. So to return to the first question of this particular session, I suggest that nav aids obviously have been improved a lot since that time and there are people here who know much more than I do about the current state-of-the-art there, but a suitable navigation aid plus an improved temperature sounding on the aircraft might meet a lot of these problems. Thank you.

Bud Irving:

Thank you, Margaret (*Haggis*). I'd like to throw one thing out here, that was suggested by one of our people. How about adding a fluorescent material to the spray mixture so that the spray pilot can see his last swath as he flies back. Anybody have any experience or care to comment on that one?

Steve Parkin:

You can hardly see it and, even with ground spraying, you have to put in a heck of a lot of dye just to see your swath on an ordinary crop, let alone in a forest. I'm afraid it's a bit too wishful thinking.

Bud Irving:

I see we're getting quite a bit of response, I guess this gentleman was first.

Unidentified Speaker:

Bud (*Irving*), what we have found in regards to this using your drift as a line to come on the next swath is using two aircraft in tandem and where one aircraft is pulling off the block and the other one is pulling back in using the last aircraft's spray as a pattern to follow and it just works excellently. We've used it in several provinces and it has proved very effective.

Alan Cameron:

I realize that at a Symposium on Aerial Spraying of Forests in Canada you are going to be focussing on spruce budworm and softwood forests, but Canadians, as well as many of those in the north east United States, are very much concerned with hardwood forest defoliators. I'm wondering if it is within bounds in just a few minutes remaining to get some comments from some of the people here on how closely what we have learned in conifer forests might relate to conditions in hardwood forests. I'm also very interested in the same kind of quick comments on relation of flat lands to, as already been mentioned by several of the speakers, mountainous situations or in our case in the eastern United States, ridge and valley situations.

Bud Irving:

There's a challenge. Anybody want to follow it up? I see two volunteers.

Unidentified Speaker:

Well I just wanted, as this particular session is related to operational conditions, to query whether all thoughts about operating at night had been put aside. In tse-tse fly control in Africa of course, currently we are operating a night-time operation with on-board navigation equipment and we are using very small droplets. The suggestion that has come out of this meeting is that the trend is toward the use of small droplets in the range, perhaps, 10 to 50 microns or even maybe, narrowing it down a bit from Prof. Spillman's suggestion, was it 15 to 35 microns. This is matching up fairly closely to the droplet spectrum we are using in tse-tse control. While we feel that we get the best results, indeed we need the stable conditions which are only available during the hours of darkness to carry out an effective treatment. So I just pose the question whether night-time operation was worth reconsidering.

Bud Irving:

With regard to this one, we have some expertise on the panel on this, but I wonder if Barry Madu would care to address that in as much as a somewhat careful assessment was made of this a few years ago by his company.

Barry Madu:

Yes, I can say that we did try it. Our problem was our undulating countryside in Canada. I'm sure that in Africa it's quite easily done. We were a little bit fearsome that we would be running into a hill sooner or later because we can't get the rate of change quick enough at night, flying as low as we were attempting to.

Bud Irving:

Thank you Barry (*Madu*).

Michel Pelletier:

Well, regarding night spraying, remember that in 1973 we did some experiments in Quebec. At that time, we were obliged to fly about 1000 feet over the highest peak in the land we were supposed to fly over. We did a few trials and in one trial, we did it in Val d'Or, and we were having a sixteen mile long layout and we recovered only one droplet. And that was due to a leaking nozzle just shooting down instead of up. We let up also balloons to check the stratification of the winds and that was the main problem. At ground level it was calm, but going up, the wind was going in different directions and at different speeds.

Bud Irving:

A bit more on this. In New Brunswick, although what Barry (*Madu*) told you was quite accurate, there was some other confounding problems on this. At that time, we were thinking of laying down a spray curtain to intercept the migration of adult moths. And this was probably going to require laying down the spray curtain on several successive nights. Regardless of the operational difficulties, both our Department of Environment and our Department of Health simply said "No Way"!

I think that Jim Warner at the back had a desire to make some comments and I think we've cut him off two or three times.

Jim Warner:

In responding to a couple of questions, in my experience, last year we used some highly fluorescent dye in one of our research projects and basically, they had a real difficult time detecting it on foliage. It was used in *B.t.* One of the things about these dyes that you have to consider is that most of them have to have additional registrations on the pesticides they're used with, or the dyes themselves have to be registered which adds a lot more things into those considerations.

The other thing is the size of aircraft and I think a lot of that information probably is more site-specific than we realize. In our contracts, our specification is basically 15 meters above the canopy as the aircraft flying height. We find that we lose probably as much as 60% additional material when he's at 30 meters or more above the canopy. In those situations, the flying height is very critical. We're operating in humidities of 50 to 65% and on the edge of some deserts. Our terrain is probably from 50 to 90% slope. We operate between 2500 to 7500 feet. So, you know, depending on what part of the country you're in, we need to look at each one of these things individually.

Bud Irving:

What category of aircraft are you referring to for these contracts?

Jim Warner:

Well, we've used from the small Hiller Saloys or even smaller than that up to the 214 in helicopters. Most of our fixed wing have been Turbo Thrushes, Ag Cats, single-engine aircraft. I have some limited experience with the multi-engined, DC-6, DC-7's and those work relatively well in ultra-low volume in grasshopper work, where you basically have relatively flat ground. Volatility is not a problem. So, in that situation, where you are doing tremendously large amounts of acreages with a chemical pesticide, then your multi-engined aircraft work relatively well. Thank you.

Chairman:

Could I just interject here — Alan Cameron never did get an answer to his question.

Alan Cameron:

I took the lack of an answer as probably the fact that we just don't know, but I was curious (*inaudible*) somebody could answer all my questions.

Chairman:

Charles (*Wiesner*), could you get into that one, because Kees (*van Frankenhuyzen*) is gone.

Charles Wiesner:

Chris (*Riley*) has his hand up.

Chris Riley:

This year we did a study in which we applied *B.t.* to three separate blocks, about 50-hectare blocks, with a gypsy moth population. Two applications were made with neat *B.t.* formulation at 30 BIU's per hectare in 1.9 litres. The other application was made with the *B.t.* diluted one part to three with water. In other words, about 7½ litres per hectare. The high volume application was applied with Micronair rotary atomizers spinning at about 3½ thousand RPM when wet. This produced a volume median diameter spray of about 240 microns. The low volume spray produced a VMD of about 90 microns in diameter. We looked at spray penetration of the canopy and also at deposit and efficacy measurements. Generally, what we found was that, in terms of spray deposition, droplets in the range of 70 to 80 microns and below were distributed well throughout the canopy, whereas the much larger droplets tended to be filtered out to a much greater extent in the upper regions of the canopy. In terms of deposit and efficacy, the low volume sprays produced at least, if not better, mortality than the high volume spray applications. That was all up in Poster Number 29.

Bud Irving:

Is there any other experience with regard to this question? I've cut into the time that you alloted to me quite severely Mr. Chairman. I don't like to cut this off.

Chairman:

Are there any more comments or questions? Charles (*Wiesner*).

Charles Wiesner:

I do have a number of comments. They're probably unrelated and some of them don't even relate to spray efficacy or aerial application. But, I thought that, maybe, if everybody else is finished it might be worthwhile before we go and have a beer just to hear me out. There is a sort of trend running through these comments. I think there is, anyway. And the trend is that we have a reality problem. I think that, in our work and perhaps in this Symposium as well, we tend to lose sight of the fact that we're dealing not only with very interesting scientific problems and very difficult scientific problems, but we're dealing with problems that really require practical solutions, problems where the people for whom this is bread and butter are crying for solutions. For all that I don't always agree with Norm Akesson, I think he's made the point very clear several times today.

Let me just run through some of these points. Perhaps in reference to, again, reality being sort of a determinant. Replying to Dr. Spillman's, one of his comments about it being very important that we validate the models with strictly controlled field experiments where only one parameter varies. I would completely agree with that. But, long before I sort of walked through the looking glass into this make believe world, I was an organic chemist for a few years and I think organic chemistry is probably about as experimental a science as you can get, and it's just not, it's just not on. You can't. An experiment in which you hold all possible parameters absolutely constant and vary only one parameter becomes a trivial experiment. It's just not reality.

A second question, a second point that I would have to make which really has nothing to do with spray efficacy relates to this Symposium. I feel that we've perhaps been a little bit naive in these discussions, particularly this afternoon. I think that this afternoon's discussion has been proceeding on the assumption that here in Canada, and with the spruce budworm in particular, and with forestry spraying in even more particular, that we are intellectually destitute, that we're devoid of ideas, we're lacking human resources, and lacking direction. I don't believe this. Let me list a few names at random and I'll obviously miss a lot of them, names most of which you will have heard this week.

Picot et al, spray modelling. Mickle et al, Lidar spray mapping. Nigam et al, larval behaviour and vulnerability. Kettella et al, field dose-response relationships. Fast et al, *B.t.* efficacy. I don't think we're intellectually destitute. I think the problem is we're politically destitute. We don't lack direction, we lack political commitment. It's been said a number of times in the last few years that forestry is far and away Canada's most important industry, that it contributes more to the economy than agriculture, mining and fisheries combined. And yet our government, our governments, past and present, treat the support of this industry and the protection of the resources necessary to this industry as small potatoes. I think we need more support for our federal laboratories and our federal scientists and perhaps even more, or as much, anyway, we need contract monies to support the very considerably body of expertise outside the federal system. Maybe this is not an appropriate place to be making this comment but I think it has to be made. It has to be made in some fashion where it can be heard. The final comment, and then I'll shut up — the gentleman, I believe he left, the gentleman from Scott Paper, has risen at least three times in this past week to ask very serious questions. I don't think he got a single practical answer. I think we need a touch of reality.

Chairman:

Well, thank you Charles (*Wiesner*). I can't remember anybody saying we were intellectually destitute. But, I can agree with much of what you say. I can assure you also that we will not follow on further on the political side here and now. What you say about the practical side of the Symposium is partly true. I have sensed that there were great expectations from operators and those closer to the operational lines that they would walk away with answers to many of their day to day problems. I think we've learned something on that side. But, I think you've got to remember, again, that we started out to address this Symposium to research gaps and research needs. So, there was some reason in that madness, if you will.

In closing this Symposium off, I said when I started this afternoon, that I wasn't naive enough to think that we are going to walk away from this thing with a set of priorized research areas that we should approach. I think we can pull some order out of what we've heard this afternoon. Everything is on tape and it's going to be looked at again and we're going to try to compress it and see if we can order something out of it. There have been some excellent contributions from the floor. I think when it's all done we'll have something that will be extremely useful.

I would just like, on behalf of all of you, to thank the Session Chairmen who have done an excellent job throughout. And I would, on behalf of the Organizing Committee, certainly like to thank the invited speakers who have come a long distance to contribute their knowledge and expertise during this week, and to those who presented Posters and those Exhibitors who are here, and to all of you who have made this a very busy and interesting and stimulating week for all of us. Thank you very much and God speed on the way home.

POSTER PAPERS

RESULTS AND PROBLEMS OF THE AIR APPLICATION OF PESTICIDES AND BIOPREPARATES IN THE CZECHOSLOVAK FORESTRY

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Forests in Czechoslovakia occupy 4,5 mill. hectares (11,2 mill. acres), i.e., 35,8% of the area of the country. Coniferous trees occupy 67% of the area, *Picea* of that 47%, *Pinus* 14%, other conifers 6%. Broad leaved tree species are on the area of 33%, of that *Fagus* 17%, *Quercus* 7%, other broad leaved trees 9%.

Air treatment of forest stands is of rich tradition in our country. The first air application of an insecticide was carried out already in the year 1926, i.e., after Canada, U.S.A., U.S.S.R., Switzerland and Germany as in one of the first countries in the world. Regular air chemical control in the Czechoslovak forestry is applied from the fourties of this century on an area 20 000 to 40 000 ha (50 000 - 100 000 acres) annually. Most frequently the forestry applied air control by insecticides and biopreparates against pests and recently also by herbicides at the weed control in forest plantations. Air application is used for fertilization, mainly lime stone at soil amelioration.

Air treatment of forest stands includes the use of airplanes and helicopters and shows in comparison with the terrestrial application a series of advantages. Air treatment of forest stands may be done also in heavy terrain conditions, where the use of terrestrial machines is very difficult or even not possible. Air application devices indicate considerably higher output so that the treatment is carried out more rapidly which is very difficult in the case of the mass outbreak of dangerous pests which may cause large economic losses. Air protection of forest stands saves labour and increases work productivity, but it is extremely necessary to keep all conditions which influence the quality and the security of the treatment. There is required exact keeping of prescribed technologies. The weather may considerably influence the result of the application of pesticides and biomeans. This concerns mainly the wind velocity and vertical air streams during the action. With respect to certain application methods there are determined maximal values for them. Another important factor is the rain which may cause the washing of the preparations, further the temperature which influences the effectiveness of preparations, sun radiation which speeds their decomposition etc.

1. AIR APPLICATION OF INSECTICIDES

Insect pests were in the past a disaster for forest stands. For instance, *Lymantria monacha* caused in the past in our country six large known calamities associated by clear eatings and destruction of Norway spruce stands on areas of thousands of hectares. First the development of air techniques and the production of insecticides meant the basic change in the control of calamity insect pests. As the insecticides indicate beside the effect on pests also more or less pronounced unfavourable effect on further components of zoocoenosis, their air application is limited only on really necessary cases with the mass outbeak of a pest which may cause important losses. The choice of the method and the process of application and the working regime depends on the properties of insecticide preparation, age and area of stands, on zoning and on configuration of the terrain. The treatment term is determined so that the most sensitive stages of the pest are hit and its natural enemies and other components of the zoocoenosis may be saved. The saving of parasites and predators is important as they are concentrated on the rest of the pest population and cause permanent reduction of its population density. The application of the insecticide is always connected with the control of the number of the pest before the treatment and after it. This control enables the assessment of the effectiveness and the economics of the air application.

The insecticides were in the past decades most frequently air applied as to control defoliators of spruce. These defoliators were of the order Lepidoptera (*Zeiraphera diniana*, *Lymantria monacha*) and of the order Hymenoptera (*Cephalcia abietis*, *Cephalcia arvensis*, *Pristiphora abietina*) and further the insecticides were air applied for the control of defoliators of the oak like those ones from the order Lepidoptera (*Lymantria dispar*, *Operophtera brumata*, *Tortrix viridana*).

1.1 Penetration of oil solutions of insecticides into forest stands

To the beginning of the 70's forest protection in our country used for the control of forest harmful insects mainly chlorohydrocarbons (DDT, Lindan) solved in oil. At the air application the usual dose was 10 l · ha^{-1} (0,892 gallon · acre^{-1}) with the content of 10% effective substance. At one flight the treated area was as a rule 50 ha (124 acres) of forest stands. This saving application method insured high work productivity and high effectivity on the larval stages or on imagines of harmful insects, usually of these insecticides on other component of the zoocoenosis we investigated the penetration of the drops of the oil solution through the space of the treated forest stand and the cover degree of spruce needles in individual vertical layers of tree crowns.

The proper measurement was based on the catching of drops of the applied insecticide on the prepared slides located in tree vertical crown strata of the 3rd age class (41-60 years) and of the 4th age class (61-80 years) with continued canopy. Afterwards laboratory measurements measured the size of the particles. Data were evaluated numerically and graphically and determination was done on the size composition of the spray spectrum and on the mean size of particles of oil solution. In further stage the number of particles per one sq. cm. area was found. The degree of the cover was derived from the density and mean size of particles.

The size of drops at the air LV spray of oil solution ranged from 1 μ to 360 μ, the most numerous drops were within the range from 1 μ to 75 μ and that from 65% to 98% of the whole number of drops. The groups of largest size of drops 100 μ - 360 μ dominated in volume.

The mean size of drops expressed by means of volume average was lowered downwards from tops of crowns. The share of drops within the range of 1 μ - 75 μ was considerably increased in the down direction. The number of drops per one sq. sm. was reduced pronouncedly in the direction from crown tops downwards to the ground, in the 3rd age class the reduction was more obvious (41115 - 150) than in the 4th age class (3068 - 180).

Percentual representation of drops within the range 1 - 75 μ:

Age class	vertical crown layer		
	upper	mean	lower
	%		
III.	65	96	98
IV.	71	88	92

The obtained cover degree was reduced from crown tops in the down direction. The reduction was higher in the 3rd age class (5,5% up to 0,6%) than in the 4th age class (5,0% up to 1,0%).

According to the measurements in upper vertical strata, in the determined volume range of the average size of particles necessary for LV spray, i.e. 50 - 250 μ and for ULV spray, i.e. 25 - 125 μ, 49 - 57%, respectively 51 - 58% of pesticide volume were produced. The claim on the production of 80% pesticide volume in the determined range was not fulfilled here. This demanded ration was held in lower crown layers where the throughfall of larger drops is difficult.

It was found that the hectare dose 10 litres oil solution is corresponding in the described stand conditions. The obtained cover at the air LV spray of the above mentioned dose of oil solution per one hectare indicates only small values in lower crown strata and if the dose per hectare is to be reduced the cover is obviously insufficient.

It was found that at the suitably determined hectare dose of insecticide and simultaneous keeping of certain accuracy at the air application (conditioned besides other factors mainly by the signalizing of air fields, correct function of the application equipment) the flow of the insecticide out of the assimilation area of trees under control need not achieve too large values and the undesired cumulation of the insecticide in soil or on other plants may be considerably reduced.

1.2 The effect of oil solutions of insecticides on birds

Investigation paid careful attention to effects of the application of oil solutions of insecticides on insectivorous birds which is of important role at the regulation of insect populations, mainly at the purposeful increase of numbers and of species representation of birds in forest stands. For instance, the control of 71 boxes — 37 were occupied by four species of the genus *Parus* — found after the application of 10 l · ha^{-1} (0,892 gallon · acre^{-1}) oil solution with content of 10% effective substance DDT that the insecticide did not kill the youngs, though mature birds searched food in forest stands treated by airplanes. In other case after the application 20 l · ha^{-1} (1,784 gallon · acre^{-1}) of oil solution with the content of 6% phenitrotione oak forest stands showed the mortality of a part of insectivorous birds. This knowledge confirms that large area and mainly repeated application of insecticides may be dangerous for birds. Persistent insecticides do not cause acute poisonings at commonly used doses, but may be cumulated in the organism and first on the second place may be the cause of the disease. Some preparations from the group of organophosphates are much more toxic, mainly at the application in the aerosol form so that the danger of acute intoxications of birds is increased. But it is without doubts that the generation changes and chronical disturbances and cumulative effects are far more dangerous than one intoxication which reduces the population density of birds species on limited area which is soon completed by the migration from neighbouring environment.

1.3 Use of insecticides diluted by water

At the beginning of the 70's in Czechoslovak forestry it was forbidden to use air control and to exceptions to apply terrestrially chlorohydrocarbons and because of water management reasons also oil in the function as insecticide vector could not be used. Insecticides for the control of harmful insects in the forest were on the phosphore basis (phenitrotione, pirimiphosmethyl) further pyrethroides (permethrine, cypermethrine, deltamethrine, cyhalothrine) and other specific insecticides (thiocyclam, diflubenzurone).

Preparations are in total formed as emulsion concentrates or as wettable powders which are diluted by water, to volume dose 50 - 100 l · ha (4,5 - 8,9 gallons · acre^{-1}). In this way the output of air equipments was considerably lowered, when at one flight only an area of 5 ha (12,3 acre) is usually treated. Also demands on technical, organisation and economic protection measures for the control of insects pests were increased. The application equipments for LV and ULV application (for instance, rotation atomisers Micronaire AU - 3000) are used only in a limited scope because of increased demands on the flight technique, necessary use of special formulations of insecticides and certain doubts about the possibility of sufficient cover of leaves and needles of forest stands by preparation drops at the application of very low volumes, usual at UV and ULV applications.

At the choice from the above mentioned spectrum of insecticides more and more stress at the air application is put not only on the achievement of reliable effect on the pest, but also on favourable toxicologically hygienic parameters of the preparations. From relatively toxic, but rapidly decomposing and as to insect non specifical organophosphates foresters successively introduced the use of pyrethroides which effect also non specifically the insects but show low toxicity for warm blooded animals. For instance at large control action against *Zeiraphera diniana* on an area of 46 000 ha (114 000 acres) in mountain conditions at the beginning of the 80's comparison was made of the effectiveness of air application of pyrethroide permethrine, mixture of permethrine and organophosphate pirimiphosmethyle and of only pirimiphosmethyle. The preparations were applied by the helicopters and consequently the effectiveness was evaluated according to the achieved reduction of egg abundance also according to the defoliation of treated stands. The obtained results are summarized in following table:

effective substance	dose in g/ha	reduction of egg number %	defoliation of forest stands %
pirimiphos. + permethrine	500 37,5	75	10 - 40
permethrine	50	72	10 - 40
pirimiphos.	500	62	20 - 50

At the present time attention is more and more turned to specifically acting insecticides, for instance, on inhibitors of the synthesis of chitine (diflubenzurone, teflubenzurone etc.) which act selectively only on certain groups of insect, for instance, on larval stages of defoliators.

1.4 Effects of air application of insecticides on entomofauna

At large area air application for the control of *Zeiraphera diniana*, investigation concretely concerned bi-effects on insects living in tree crowns, further on insects of the herbaceous layer, on insects flying above ground surface and on insects of soil surface and in soil and further on insects in water streams and on vertebrata. The effect of the air treatment was studied by comparison of the number of investigated species on treated and on untreated areas. The maximal mortality of insects and spiders was found in tree crown space, the target area of the control insecticide. Beside the mortality of 80 - 87% caterpillars of the pest *Zeiraphera diniana*, investigation of a plot 1 m^2 showed 70 to 230 specimens of non-target species of Arthropoda. Numbers of flying insects above the ground surface, mainly representatives of the genus Diptera was reduced during some days to 20 - 30% in comparison with the control and its number begun to be again increased after a fortnight after the application. The influence on the insects of the soil surface was not found, obviously because the insecticide did not penetrate to the soil through crowns of the treated forest stand and through the herbaceous layer. Likewise differences in the representation of individual groups of soil fauna on treated and control plots were not found. The pronounced effect of the treatment was found in the fauna of creeks. The number of effected larvae of water insects transferred by the stream was rapidly increased after the application and achieved 10 to 30 times larger quantity than it is normal. The spraying hit water insects sensitively, but no species was fully destructed as later investigation on application localities showed. The influence on vertebrata was minimal. As conclusion it may be stated that single air application of an insecticide showed also unfavourable consequences but did not destruct the investigated components of the ecosystems.

1.5 Air application of wood blown down

In recent years after the repeated catastrophic windfalls the danger of the mass outbreak of bark insects was increased. This concerned mainly the bark beetle *Ips typographus* which then attacks also standing spruce stands. As to prevent the attack of lying windfall and the rapid mass outbreak of *Ips typographus* on suitable localities preventive air spraying of windfalls by helicopter was tested, in the time closely before the swarming or at the beginning of the swarming of the above mentioned pest. Simultaneously with preventive wood protection also the number of bark beetles was reduced. This concerns bark beetles which fly onto the lying wood. Applied pyrethroides were permethrine and cypermethrine in the dose 200 g · ha^{-1} (0,178 pounds · $acre^{-1}$). Better dispersion and adhesivity of spray drops were achieved by wetting agent in 1% concentration. At the application it is required that the helicopter may fly as low as possible and slowly above lying trees as the cover by drops on stem surface may be the most perfect one. At the flight height of the helicopter 10 m above the windfall and at the flight velocity 40 km · h^{-1} the intensity and uniformity of the treatment are satisfactory in the working belt 30 m broad. The destruction effect on imagines of *Ips typographus* persisted for a period of 2 to 4 weeks. This method is determined for the use in species cases, not generally.

1.6 Economic effectiveness of air application of insecticides

Insect pests cause by their eating on trees the death of trees, may be disturbances in physiological processes which appear in the reduced resistance and in the fall of the increment. It is a general matter that air treatment in time is to prevent the development of the outbreak of pest and the rise of injuries on neighbouring forest stands. As the insecticides show also bi-effects which are unfavourable and air application is expensive, it is useful to carry out the protection treatment only when it is obvious that the mass outbreak cannot be destructed by natural way, though the height of assumed injuries caused by insects exceeds the costs of air treatment. The evaluation of the prevention is to be based on the relation between the growth reaction of the tree species and the damage of leaves and needles as one of the fundamental questions.

In southern Moravia the mass outbreak of nun moth (*Lymantria monacha* L.) included an area of about 1 500 ha. The mass outbreak of temporatory type menaced to grow into larger clean feedings and for this reason it was necessary to apply chemical control after shorter time of feeding. We used this locality for the determination of increment losses after defoliation of Norway spruce forests by short time feeding of defoliators. The processing of 556 borings from sample trees in polluted and control forest stands offered sufficient basis for biometric evaluation of increment changes by dendroecological method. We investigated mainly increment reaction on variously intensive defoliation in forest stands of various age. The secondary question was, if the different increment reaction at trees occurs according to their position in the forest stand structure. The evaluation resulted in following conclusions:

The size of increment losses is directly proportional to the reduction of assimilation mass in tree crowns attacked by feeding. After rounding off these increment losses in two years of maximal effect of feeding at defoliation represent up to $^1/_3$ of assimilation mass of crown 30%, at defoliation between $^1/_3$ to $^2/_3$ of green mass 50% and at the loss of needles larger than $^2/_3$ of crown 70% of increment of control forest stands not harmed by feeding. The increment losses are, of course, spread on longer period and even at the third growing season after the chemical treatment resulting in the destroying of pest population the restution of the increment in more defoliated forests has not achieved the normal increment level of unharmed forests. On the average of the last five year period the increment losses are scaled according to feeding degree in the ratio about 20%: 35%: 50%.

Relative increment losses derived from the development of the diameter increment may be — based on the conversion to concrete survey units and size of forests harmed by various degree of feeding — used for the expression of production losses due to feeding of defoliators (in cu.m./ha/years), or for economic evaluation of these injuries in forestry. This method serves mainly at the evaluation of economy and at the choice of individual forest protection measures in the complex forest protection.

Concrete evaluation of the size of increment losses and average price of wood and their comparison with the costs of air treatment of one hectare of spruce stands resulted in the fact that already at the weakest degree of the clean eating the loss value exceeded in the increment the costs three to four times the expenses of the air treatment, at the mean eating then three to seven times and at the strongest eating already 7 to 11 times. The economic evaluation indicated that air treatment in time, already at the beginning of mass outbreak was in this case economically effective.

2. AIR APPLICATION OF BIOPREPARATIONS

At the selection of preparations for air control of forest insect pests the researchers more and more into consideration criteria connected with nature protection. In the Czechoslovak forestry there appear more and more the efforts to limit the non specifically acting preparations and to replace them by preparations which are of selective effects on certain insect groups, are not toxic for vertebrata and resistance does not develop. A principle of the destruction of only such number of the pest was to be applied which is necessary for the keeping of balance in the forest. At the present time biopreparations on the basis *Bacillus thuringiensis* offer the largest possibilities for the use in the control of caterpillars of butterflies eating in forest stands. They do not possess the destructive effect on caterpillars as chemical insecticides, but indicate selective effect on caterpillars of butterflies and save other insects, mainly parasites and predators and are unharmful also for other components of the ecosystem. The comparison result of the effect of the air application of biopreparation *Bacillus thuringiensis* and chemical insecticides is listed in the following table:

Number of killed insects at the control *Zeiraphera diniana* (1980)

Group	Number per 1 m^2		
	Bac. thuring.	pirimiphos-methyle	permethrine
Z. diniana	78	172	462
Diptera	2	16	37
Homoptera	—	33	21
Hymenoptera	—	9	7
Coleoptera	—	1	6
Heteroptera	—	3	—
Aachnoidea	—	1	2
In total	80	235	535

At the present time we use in our country common smaller and larger control measures based on air techniques — air planes and helicopters. Control methods are processed for *Tortrix viridana, Operophtera brumata, Zeiraphera diniana, Lymantria dispar* and we test possible use for the control of other pests, for instance *Orgyia recens* and of gnats.

Use is made of foreign preparations Dipel, Thuricide HP, Teknar and of home preparations Bathurin 82 and Moskytur. Biopreparations are formulated like wettable powders or colloid liquids and are applied diluted by water in spray form, in volume doses 50 to 200 l · ha^{-1} (4,5 to 17,8 gallon · acre^{-1}) containing 1 - 2 kg biopreparation. The preparing of the spraying emulsion is at the powder biopreparation more labourious so that at air application is necessary to use special mixing device. The powder biopreparation is to be slowly strown into the mixing container with only one quarter of water which is to be completed after the mixture is made. At the use of this mixing device the air application was not slowed down. As the viscosity of the spraying suspension is to be in certain limits because of correct function of air application device, it is necessary to select satisfactory dilution of the biopreparation by water and that means relatively high volume of spraying suspension which also secures sufficient quality of the cover of treated forest stands by bacterial preparation. Researchers search possibility of the effective use of assistant substances for the better dispersion and adhesion of the bacterial preparation on assimilation organs of forest trees.

In the spring period when usually application of biopreparations occur, the weather in Central European conditions is unstable and mainly the temperature ranges at the lower limit unfavourable for the infection development of *Bacillus thuringiensis*. For that reason we search possibilities how in these conditions reliable effect of air application of biopreparations is to be secured. One of the ways is the search and use of synergic effect with the sublethal dose of suitable chemical insecticides and this so that the effectiveness satisfactory for caterpillars of the pest may be secured and assimilation organs of trees may be protected and simultaneously the satisfactory effect on non-target insects may be maintained. The result of the experiment is given in the following table:

Comparison of the effect of experimental variants on other insects (1977)

Group	Bac. thuring.	Bac. thur. + permethrine	permethrine
Lepidoptera	124	136	123
Hymenoptera	—	8	45
Coleoptera	—	10	90
Diptera	2	30	150
Other	—	2	112

3. AIR APPLICATION OF HERBICIDES

The large extent of wind calamities after the year 1984 caused not only large dimensions of calamity fellings, but also unusually large extent of clear cut areas. These facts caused unusually large size of works with soil preparation for afforestation and weed killing in forest plantations. These operations done in time secure successful afforestation of clear cut areas. Serious problem is connected with the protection and care of new forest plantations in regions with concentrated calamity fellings where hitherto used technologies based on mechanical killing of weeds and spot application of herbicides are not satisfactory. For that reason air application with acceptable hygienic-toxicologic parameters was introduced. The target is to secure conditions for successful establishment and growth of the forest stand in hundred years period by one application of minimal necessary dose of herbicide. So comprehended use of chemicals is in our forest considered as acceptable, economic and necessary measure.

On areas determined for the afforestation there is broad spectrum of mostly permanent herbs and shrub as well as tree weeds. Perennial grasses are frequent. Only helicopters are used for air application. At weed killing on plots determined for afforestation and directly in plantations we are to consider not only the mostly negative influence of the weed but also its importance for soil erosion control and as the source of wildlife food. For that reason it is necessary at the choice of herbicide and the size of its application to respect beside economic targets also ecologic sides in regions with different natural conditions of food for game. For that reason it is necessary when selecting the herbicide and the extent of its application to respect beside the economic target also ecological points of view in regions with different natural conditions and mainly water conservation.

At the present time the most applied preparations for weed killing on forest soil are those ones on the basis of hexazinone (wettable powder, emulsion concentrate, granulate) and glyphosate (emulsion concentrate) which indicate non-selective wide spectrum of effect on herbs from Monocotyledonae and Dicotyledonae and on broad leaved trees and *Larix* and in recommended doses are tolerant to the most distributed conifers — *Picea, Pinus* and *Abietis*. But they cannot be applied at the growth of broad leaved trees and *Larix* which are tree species securing larger stability of future forest stands. In further years also the representation of *Quercus, Fagus* and *Acer* is to be increased. For these reasons the promising is preparation on the basis of fluaziphope - butyle (emulsion concentrate) which may be used without risk of damage on conifers and broad leavers on plots with dominating grasses which are selectively killed.

3.1 Air application of herbicides diluted by water

At the air application of herbicides in the spray form there is of increasing risk the transfer of herbicide outside the target plot. This transfer is influenced mainly by weather conditions and the working règime of application. From meteorologic factors the decisive ones are mainly wind and temperature radiation inversion.

The unprecise application of herbicides due to unfavourable weather conditions and unsuitable operation règime may be prevented by the determination of limit values of weather conditions and of flight height. Further it is recommended to use nozzles which produce large drops with mean volume diameter 300 μ and larger. As to keep the requested relation between the size of drops, cover of plants and the biological effectiveness of the herbicide it is necessary to apply volumes 100 to 200 l · ha^{-1} (8,9 – 17,8 gallon · acre^{-1}) from the height 10 m.

The limit values of weather conditions at the spraying of herbicides:

Hexazinone — permitted wind velocity to 2 m · sec^{-1}, air temperature 1 to 25°C, soil must not be frozen, nor covered by snow, slight rain at the application is not obstacle.

Glyphosate — permitted wind velocity to 2 m · sec^{-1}, air temperature 10 to 25°C, relative air moisture minimally 50%, rain to 6 hours after the application reduces the effectiveness.

Fluazifop-butyle — permitted wind velocity to 2 m · sec^{-1}, air temperature 10 to 25°C, relative air moisture minimally 50%, rain to 30 minutes after the application reduces the effectiveness.

Conditions of temperature radiation inversion are fully unsuitable for air application of water emulsion of herbicides. The sedimentation of drops is considerably more difficult and the herbicide may be unsuitably transferred to large distances. Inversion conditions may be as to orientation indentified according to the smoke which does not rise and remains at the ground without movement.

3.2 Air application of herbicides in granulate form

As the wind is at the air application of herbicide the decisive limiting factor which often makes the application impossible or reduces it, researches searched the mode how its effect is to be lowered. From that reason the application of granulated preparation (hexazinone) was tested. The assumption for the application was that granules with higher specific weight may be more precisely located also at stronger wind than spray drops. As the carrying substrate of herbicide there was used silicious sand with grains in the size of 0,6 to 1 mm with specific weight 1,45. Five percent active substance hexazinone is bound to sand grains.

For the application of the granulate tests were carried out on the application equipment consisting of two drills — rotation discs carried by the helicopter. Before the proper application investigation at the testing flights concerned total width of the spread, width of the working zone and uniformity of the spread at the operation zone in the flight height 10 m and 20 m and at the flight velocity 60 km · h^{-1}. The target was the determination of the most suitable working règime for the application of necessary doses (30 kg granulate · ha^{-1}). At the testing flights the spread granulate was caught into collecting cones and according to the weight quality the preparation dose per hectare was found. The results showed that the uniformity of the spread of granulate is better at the application from the height 20 m, when the width of the working zone is 20 m. On the basis of tests following working règimes were determined:

a) For the application on the unforested clear cut areas: Dose per second 1,03 kg granulated herbicide, flight height minimally 20 m, flight velocity 60 km · h^{-1}. Dose per hectare under these conditions makes 30,8 kg granulated herbicide.

b) For the application on the unforested clear cut areas: Dose per second 1,03 kg granulated herbicide, flight height minimally 20 m, flight velocity 70 km · h^{-1}. Dose per hectare under these conditions makes 26,5 kg granulated herbicide.

Limit values of weather conditions for the air application of granulated herbicide:

Hexazinone — permitted wind velocity to 4 m · sec^{-1}, air temperature 1 to 25°C, soil must not be frozen nor covered by snow, slight rain at the application is no obstacle.

The evaluation of results of terrain application of granulated herbicide with the active substance hexazinone shows that weed was killed on 50% area of treated plots, on 30% of the area the weed was weakened. The results contributed to the establishment of a new forest on calamity clear cut areas.

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FIGURE 1: WEEDS IN A TWO YEARS OLD PLANTATION OF SCOTS PINE *PINUS SYLVESTRIS* BEFORE THE AIR APPLICATION OF HEXAZINONE

FIGURE 2: HELICOPTER MI-2 AT THE APPLICATION OF HEXAZINONE (1,35 kg ACTIVE SUBSTANCE/200 L WATER PER HECTARE)

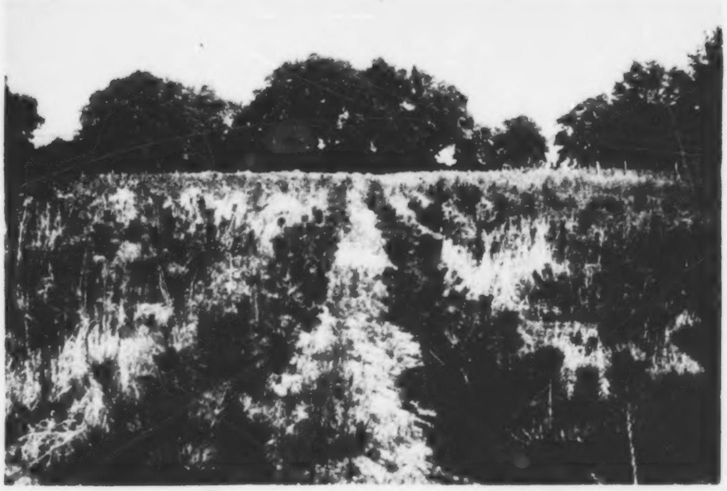

FIGURE 3: EFFECT OF HEXAZINONE TWO MONTHS AFTER THE APPLICATION

The Table 8 results show a pronounced reduction in ground deposit (well demonstrated in the field trial data of Table 6) going from the very stable to the unstable situation with maximum canopy deposit showing up in the unstable case. Increased vertical motion of turbulent eddies under unstable conditions provides the optimum situation for maximizing canopy deposit. These conditions occur shortly after sunrise when thermal heating of the trees quickly creates an unstable zone at low altitude.

CONCLUSIONS

The PKBW model gives very good results for prediction of droplet deposition on coniferous foliage and ground for the best terrain considered here where tree cover is predominantly coniferous. It is currently being used to carry out computer investigations of the affects of operational modifications in forestry spraying by the New Brunswick Spray Efficacy Research Group. The obvious importance of aircraft height has been recognized. However, aircraft vortex strength is shown to be important. Higher strengths permit the droplet cloud to be projected into the canopy before significant dispersion. Optimization of aircraft type and aircraft operation then becomes possible. Plans for testing heavier fixed-wing aircraft and helicopters are under way. Preliminary tests will be done with the PKBW model, followed by field trials. The objective is increased foliage deposit and reduced off-target drift. Significant improvements seem possible.

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Note in Proof

1) Modification of the model for the unstable case has led to appreciably different results. The model has not been rerun with the modified version for the unstable scenarios listed in Table 4, however, reruns for other studies involving unstable conditions have indicated that in general, canopy deposit is increased by approximately 100%, ground deposit is negligible, and drift is reduced.

2) The model is not well behaved under unstable conditions: there is an artificial bias for material to drift downward into the canopy. Thus, predictions in canopy deposit may be artificially high.

In this respect, improvement in the model is required.

DISTRIBUTION OF DEPOSIT IN AN OAK FOREST FOLLOWING AERIAL APPLICATION OF *BACILLUS THURINGIENSIS*

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ABSTRACT — A 10.1 ha hardwood forest stand was aerially sprayed with 29.6 BIU/ha of *Bacillus thuringiensis* (Bt). Leaves were sampled individually from 10 sample trees to examine the distribution of deposit within the canopy using fluorescent tracer and image analysis techniques. Artificial targets above the canopy showed significant variation in the deposit arriving above sample trees. A high degree of variation with no significant differences was found in the mean deposits at upper and lower canopy levels, also with directions within a level. Spray deposit was lognormally distributed between leaves. Image analysis was found to be an accurate deposit measurement tool, yielding both quantitative and qualitative information on spray deposit on a single leaf basis. Dose measurements on the basis of droplet density and percent area covered were both linearly related to dose on a volume per unit area measurement.

RÉSUMÉ — Un peuplement de feuillus de 10,1 ha a été traité avec *Bacillus thuringiensis* (BT) par pulvérisation aérienne à raison de 29,6 UBI/ha. On a prélevé des feuilles individuellement sur 10 arbres échantillons pour examiner la répartition du dépôt à l'intérieur du couvert, à l'aide de techniques faisant appel à des traceurs fluorescents et à l'analyse d'images. À l'aide de cibles artificielles situées au-dessus du couvert, on a constaté une variation importante de la quantité arrivant au-dessus des arbres échantillons. Les dépôts moyens présentaient un degré élevé de variation, sans différences importantes, aux niveaux supérieurs et inférieurs du couvert ainsi que dans les différentes directions à un niveau donné. Le dépôt pulvérisé était réparti de façon log-normale d'une feuille à l'autre. L'analyse d'image s'est révélée un outil efficace pour la mesure du dépôt; elle fournissait des renseignements quantitatifs et qualitatifs sur le dépôt sur chaque feuille. Les mesures de la dose basées sur la densité de gouttelettes et sur le pourcentage de surface couverte étaient toutes deux linerairement reliées à la dose mesurée en volume par unité de surface.

Delivery of pesticide by aerial application to forest terrain is one of the most difficult forms of aerial application. Many factors effect the spray distribution in the canopy. Among the most significant are human factors such as pilot accuracy and nozzle choice, the prevailing microclimate, and the physical structure of the canopy. With insecticides, the resultant deposit distribution should be assessed with regard to the interaction between the dynamics of the spray toxin and the behavior of the target pest. In the case of *Bacillus thuringiensis* (Bt), the microbial pesticide must be ingested before the toxic moiety can be activated to become an effective pesticide. With forest defoliators, the route for delivery to the insects' digestive tract must be via the leaf feeding site. Thus, spray distribution between leaves becomes an important aspect of pesticide effectiveness. In the case of the gypsy moth, *Lymantria dispar*, L., the larval stage is highly mobile and is able to move between leaves, possibly in an effort to optimize feeding and survivorship. Ideally, to maximize the probability that the foraging larvae will encounter and consume the treated leaves, the spray should be distributed evenly between the leaf feeding sites.

Only a few studies have been conducted to measure the mean spray deposit within a hardwood canopy. Dunbar et al. (1973) measured the mean deposit at three canopy levels (top, middle, and bottom). They found the mean deposit was 42.7 IU/cm^2 for the top level of the canopy. This mean deposit was reduced to 29.4 and 29.7 IU/cm^2 at the middle and bottom levels. However, these differences in deposit where not significantly different. Maksymiuk et al. (1973) also demonstrated higher deposit levels at the top of the crown compared to leaves sampled at four directions within the crown. Our work has extended these studies by using more extensive sampling and detailed analysis, including the use of image analysis of spray deposits.

OBJECTIVES

The objectives of this study were (1) To quantify the deposit found throughout the canopy measured in terms of an amount of toxin per unit leaf area (International Units/cm^2). This quantification process was designed to identify a) the difference in spray exposure to each sample tree, b) the difference in mean canopy deposit in the upper and lower canopy strata and between horizontal positions within a stratum, and c) the distribution of the dose between individual leaves within a tree. (2) To determine the droplet size and droplet density distributions in the upper and lower canopy levels, and (3) To compare an image analysis technique with a fluorescent tracer wash-off method. Comparisons were made using the fluorescent technique as a standard and then relating the various deposit characteristics to that standard.

MATERIAL AND METHODS

Plot Description

The spray plot was located at Black Moshannon, Pennsylvania. The predominant species where Red Oak (*Quercus rubra*) fam. Fagaceae, White Oak (*Quercus rubra*) and Red Maple (*Acer alba*) fam. Aceraceae.

The plot was 10.1 ha (25 ac) in area, each side 323 meters (1050 feet). A buffer zone of 200 feet was maintained between the plot boundaries. This allowed a margin for displacement of the swath horizontally by a wind component. Applications were made on June 3, 1986 at 8:00 a.m. Leaf expansion was approximately 70%.

Aircraft

Applications were made using a Cessna Ag-truck, a 300 h.p. fixed wing (41 feet 8 inches) agricultural aircraft (supplied by the USDA, Animal and Plant Health Inspection Service). Speed during application was 115 m.p.h. using a 75 foot swath width. All applications were made at 50 feet above the canopy. Flight lines were made in-line with the wind directions and followed helium filled balloons placed at 150 feet intervals down both the up-wind and down-wind sides of the plot.

Spraying Systems 8004 stainless steel flat fan nozzles were used at 40 pounds per square inch (psi) pressure and directed 90 deg to the airstream. Droplet characterization with water at 100 mph produced a nmd of 61 μm and a vmd of 242 μm (Yates et al. 1984).

Formulation

Thuricide 64LV (Sandoz Crop Protection Inc, Wasco, CA) was applied at 29.6 Billion International Units/ha (12 BIU/ac) in 7.1 l/ha (96 fl. oz/ac). The tracer Brilliant Sulfaflavine FF (Organic Dyestuffs, East Providence, RI) was added at 8.64 g/l of final spray mix. The tracer was recovered from each leaf by shaking for 20 minutes with 75 mls of 30% aqueous methanol. The tracer concentrations applied were measured from tank samples taken from the aircraft spray boom after completion of spraying.

Canopy Sampling

Ten sample trees (*Quercus* spp.) were conceptually divided into an upper and lower strata. Each of these levels was divided into 4 quadrants. These quadrants were aligned parallel with and perpendicular to the flight direction. From each of these four quadrants, at each level, branches were removed by tree climbers, providing a sample in excess of 100 leaves. From this sample a random selection of 15 leaves was taken for fluorometric analysis of spray volume per leaf area. Determination were made on each leaf. Five additional leaves were photographed for image analysis. This sampling scheme provides 160 leaves from each tree (2 levels, 4 lateral positions and 20 leaves per position). Deposit per unit leaf area was calculated on an individual leaf basis by measuring the amount of tracer on each leaf and dividing by the area of that leaf as measured using a Licor 3000 leaf area meter.

Artificial Targets

Artificial targets were used to sample the spray arriving above the canopy and at ground level. Horizontal plates (102 × 128 mm) were divided to give half the surface as acetate (0.005 mm thickness), used for fluorescent washoff, and half as Kromecote card for image analysis. This size and orientation of the collector does not represent the most efficient collector of air-borne droplets, but provides a convenient target for deposit measurement using automated image analysis. These targets were not intended as absolute measures of air-borne deposit, but as indicators of the relative exposure of each tree.

Above canopy collectors were positioned 3 feet above the canopy top on a horizontal cross-beam. Four collectors at a 0.46 m interval were placed on each cross-beam and were erected the day prior to application. No directional standard was possible because of the difficulty in attachment.

Ground-based samplers were mounted on wire stakes 3 feet above the forest floor, and were aligned beneath the four canopy quadrants at approximately the dripline of the sample tree.

Leaf Photography for Droplet Size Assessment

A permanent record of droplet deposit was made using 35 mm photography. Photographs were taken using a Nikon FE 35 mm SLR camera with a Micro Nikkor Macro lens. The lighting used to excite to the fluorescent tracer was long wave (ca. 420 nm) ultra-violet (Mite-Lites inc, MA). Fujichrome 100 (ISO 100) daylight type substantive color-reversal film provided the desired properties for a very sharp image and fine grain texture. Calibration was established by photographing a series of photographically reduced circular spots of precisely known size (100 - 550 microns size).

Image Analysis

An Optomax V image analyser (ITI, Burlington, MA) was used to measure deposit characteristics. Custom software was used to calculate IU/cm^2, droplets per cm^2, percentage of the total leaf area covered and drop spectrum characteristics. Stains below 3 pixels (36 μm) were discounted during the image processing stage because of having a low probability of being a droplet. Data was recorded on a single leaf basis taking 100 drops or 100 images per leaf, whichever occurred first.

Droplet diameter for sizing was calculated using the stain area. Each stain area was converted to a diameter then adjusted to an airborne droplet diameter using a spread factor. The spread factor was determined under field conditions by graphically comparing the difference in shape of cumulative number distributions from magnesium oxide slides (May, 1950) and artificial targets placed adjacently on the canopy floor. Once converted to a diameter the droplet could be allocated to a sizeclass. A total of 20 droplet size classes arranged in a root two progression starting with an upper size limit on bin #1 of 10 microns were used to construct a droplet distribution.

Weather

Meteorological measurements were recorded at 50 feet above the canopy using an air-borne sensor mounted below a 2.25 cubic meter directional balloon. Results were relayed by radio telemetry to a ground station (ADAS, Atmospheric Research, Boulder, CO) and recorded on cassette for later analysis. Periodic measurements were also made on the dry bulb temperature and humidity at 3 feet above ground level measured using a max/min thermometer and a solid state hygrothermograph.

Analysis of Data

The variables of volume per unit area, number of droplets per unit area, and the drop size parameters nmd and vmd were transformed by logarithms to the base 10 to produce a normal probability distribution for analysis.

Results are expressed in terms of a) International Units per cm^2 (IU/cm^2) which represents the dose per unit target area, b) droplet density (number/cm^2) which represents the number of droplets, regardless of size, per unit target area, and c) droplet size (microns) which is represented by the 50% [median] levels for both number and volume. Means and standard errors are quoted on the transformed scale. A geometric mean which has been transformed back to the original scale is also given (Steel and Torrie, 1980).

Variation in above-canopy deposit was determined by ANOVA. The above-canopy artificial collectors were designed to provide a one-way ANOVA using 4 samplers per tree for replication. The difference in mean deposit within the canopy was tested with a mixed effect model with treatments (positions in the canopy) arranged in a factorial design.

Individual leaf deposits, which could take any value from zero to the maximum deposit found in the canopy, were allocated to deposit classes to form a frequency distribution. This distribution estimated the proportion of the leaves in the canopy which were likely to receive a deposit within defined deposit ranges.

All deposits were first transformed to logarithms. Thirty deposit classes where constructed on a logarithmic scale starting at an upper class limit of 0 (1 IU/cm^2) and incremented in steps of 0.1 up to 2.9 (794 IU/cm^2). Percentage frequency and cumulative distributions were then constructed. A logit transformation, $p = \ln(p/[1-p])$ where p is the proportion of leaves in a deposit class, was applied to percentages in the cumulative distribution.

Droplet spectrum was characterized by a nmd and vmd. A paired *t*-test was used to compare either the nmd or vmd between upper and lower canopy levels at a given quadrant position. This technique uses the difference in median value (nmd and vmd) between upper and lower canopy levels as a normal independent variable, thus eliminating between-tree sources of variation.

Linear regression was used to establish if the estimates of mean deposit at a position in the canopy were equivalent for both fluorescent and image analysis measuring techniques. Variables used were log 10 (IU/cm^2) calculated from image analysis and fluorometric techniques. If the deposit estimates were the same for both techniques then the slope of the regression would be equal to 1. This was tested with a *t*-test.

The alternative deposit measurements, droplet density and percentage of leaf area covered, were also compared with the direct volume estimated by fluorescent washoff using linear regression.

RESULTS AND DISCUSSION

Weather

Summary results of the weather, averaged over a period starting 5 minutes prior to application and finishing 10 after application at 50' above the canopy the condition, were as follows: wind speed was 1.8 m/sec, wind direction 57 deg., dry bulb temperature 5.3°C, wet bulb temperature 5.2°C, relative humidity 98.3%, pressure 948.8 mBar. Ground conditions were dry bulb 4.5°C and 81.6% relative humidity.

Spray exposure from above canopy and ground level targets

Using ANOVA a highly significant variation was found in the amount of spray arriving above the canopy on the artificial collectors of the ten trees sampled ($F = 20.90$, df 9,30, $P > F$ 0.0001). This may have been due to either position of the sample tree with respect to the aircraft flight line, or random turbulent displacement of the spray within the swath. Mean of the transformed deposit was 2.158 IU/cm^2 (±SE 0.3412; geometric mean = 143.847 IU/cm^2). The maximum deposit per area calculated for a uniform application to a flat surface with 29.6 BIU/ha is 296.5 IU/cm^2. This represents only a 48.5% recovery, but this may be due to a combination of drift loss and the collection efficiency of the flat plates. The mean of the transformed deposit at ground level was 1.397 IU/cm^2 (±SE 0.2208; geometric mean = 24.945 IU/cm^2).

Within-canopy partitioning of foliage deposit

A highly significant third order interaction was found between tree, level and position. Further second order interactions for tree-by-level and tree-by-position were also highly significant (Table 1). This indicated that there was little consistency in the relationship between location in the canopy and mean deposit.

TABLE 1: Results of ANOVA on canopy deposition in an oak forest using a factorial treatment design.

Source	F	df	P>F
Tree	2.780	9,1120	<0.001
Level	0.867	1,9	0.376
Tree * Level	1.513	9,1120	0.250
Position	1.154	3,27	0.345
Tree * Position	6.572	27,1120	<0.001
Level * Position	0.981	3,27	0.416
Tree * Level * Position	2.878	27,1120	<0.001

Given these interactions it was not surprising to find that the level and position main effects were non-significant. Thus, there was no difference in mean deposit either between levels in the canopy, or between positions within a particular level. Although Dunbar et al. (1973) and Maksymiuk et al. (1973) found highest deposits in the tops of the canopy, they also found no significant differences between canopy levels in both experiments. This does not agree with the work of Joyce et al. (1979) in pine stands who found reduced deposits lower in the canopy.

There was a significant difference in the mean foliage deposit between the sample trees. This may reflect a combination of the different amounts of spray available for capture, as shown above, and the different canopy structures and leaf densities.

The deposit means for different levels are shown in Table 2. These demonstrate the lack of a trend in the partitioning of the deposit between the upper and lower canopy levels. The low mean foliage deposits in this trial, compared to the spray arriving above the sample trees, represents the diluting effect of a leaf area per hectare greater than one and the incomplete capture of spray by the canopy and subsequent ground deposit.

TABLE 2: Mean spray deposit for upper and lower levels in the canopy.

	IU/cm^2 Deposit							
	Upper Level				Lower Level			
Tree	Number Leaves	Mean*	± SE	(Mean)	Number Leaves	Mean*	± SE	(Mean)
1	59	1.47	0.45	(29.51)	57	1.67	0.41	(46.77)
2	60	1.75	0.46	(56.23)	60	1.75	0.39	(56.23)
3	60	1.55	0.30	(35.48)	60	1.59	0.33	(38.90)
4	60	1.45	0.35	(28.18)	60	1.45	0.24	(28.18)
5	60	1.32	0.24	(20.89)	60	1.29	0.30	(19.50)
6	60	1.34	0.36	(22.91)	60	1.42	0.35	(26.30)
7	60	1.12	0.62	(13.18)	56	1.44	0.45	(27.54)
8	60	1.48	0.44	(30.20)	59	1.21	0.33	(16.22)
9	60	1.62	0.22	(41.69)	60	1.69	0.25	(48.98)
10	60	1.27	0.35	(18.62)	60	1.21	0.32	(16.22)

* Numbers are logarithms$_{10}$ of deposit (IU/cm^2) with untransformed means in parentheses.

Distribution of dose between leaves

Both upper and lower canopy leaves show a lognormal probability distribution of deposit (Fig. 1). Uk and Courshee (1982) have also shown a lognormal profile sampling in a cotton canopy. This justified the use of a logarithmic transformation of the data prior to analysis. Presentation of mean deposit values without transformation is likely to overestimate the effective mean deposit due to bias produced by the small fraction of heavily dosed leaves.

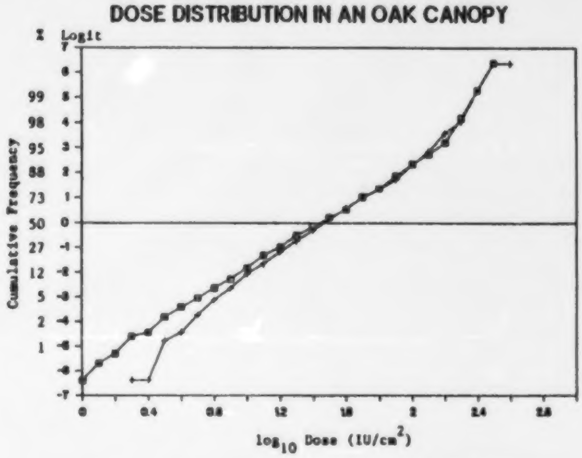

FIGURE 1: CUMULATIVE DISTRIBUTION OF DEPOSIT SHOWING PERCENTAGE OF LEAVES HAVING DEPOSIT LESS THAN STATED VALUES: ☐ UPPER CANOPY; + LOWER CANOPY.

The upper and lower canopy deposits were very similar in median dose (1.448 IU/cm^2 compared to 1.460 IU/cm^2 respectively). The cumulative frequency curves were also very similar in shape, suggesting little difference in the way the deposit was distributed between leaves in the upper and lower canopy of the sample trees. This concurs with the above findings (Table 1) that there is no overall difference in either the dose level or the distribution of that dose between upper and lower canopy levels.

Image analysis

The spread factor used was calculated as a function of stain diameter using the following relationship: Spread factor = 1.054 - 0.00174. (Stain) + 1.24 × 10^{-6}. (Stain)^2. Limits for this function were set between 0.427 (the minimum) and 1. The spread factor estimated by this function was multiplied with the stain diameter to produce a droplet diameter.

Mean logarithmic droplet density for the different levels in the canopy was 0.703 droplets/cm^2 (SE±0.059; geometric mean 5.047 droplets/cm^2) for the upper canopy and 0.754 droplets/cm^2 (SE±0.003; geometric mean 5.675 droplets/cm^2) for the lower canopy. Similarly, mean logarithmic percent area covered was -0.974% (SE±0.046; geometric mean 0.106%) for the upper level and -1.036% (SE±0.044; geometric mean 0.092%) for the lower level.

Droplet size was characterized using nmd and vmd with the median sizes given as means of logarithm of size. Upper canopy nmd was 1.991 μm (SE±0.011; geometric mean 97.95 μm) and 2.221 μm (SE±0.008; geometric mean 166.34 μm) for vmd. Lower canopy nmd was 1.975 μm (SE±0.009; geometric mean 94.40 μm) and 2.173 μm (SE±0.008; geometric mean 148.93 μm). The difference in upper and lower canopy droplet sizes was not significant (t=0.97, df=15; P>t=0.339 for nmd and t=1.62, df=15; P>t=0.114) for vmd.

Comparisons of the image analysis technique showed a very good agreement with the fluorescent washing technique on the basis of a volume-for-volume comparison. The mean volume from 15 leaves taken at one tree location was compared with the mean volume estimated from the image analysis of 5 leaves taken from the same tree location. An initial regression showed the β_0 (intercept) coefficient to be nonsignificant; that is, the regression line passed through the origin as would be predicted (t=0.241, df=1; P>t=0.115). Further regression with a simplified model containing only the β_1 (slope) coefficient gave the following relationship: $\mathrm{Vol}_A = 0.977 \cdot \mathrm{Vol}_F$ where Vol_A was the volume calculated from image analysis and Vol_F was the volume calculated by fluorescent analysis. This slope was not significantly different from 1 (t=1.25, df=78; P=0.05). This relationship is shown in Figure 2.

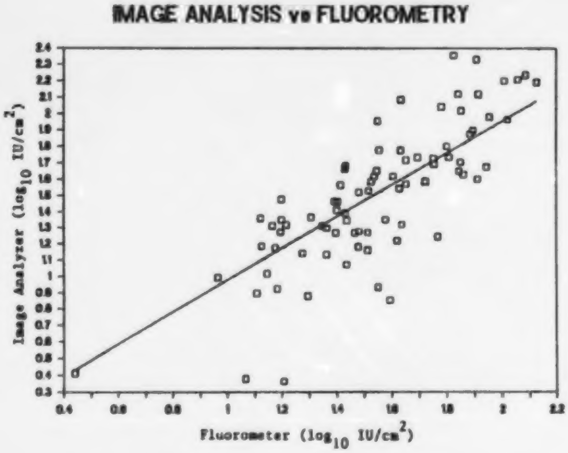

FIGURE 2: RELATIONSHIP BETWEEN DEPOSIT PER UNIT AREA (IU/cm^2) MEASURED BY FLUORESCENT TRACER AND IMAGE ANALYSIS TECHNIQUES.

The regression between mean droplet density and mean fluorometer washoff also showed a significant relationship. Again the intercept was non-significant (t=-1.268, df=1, P>t=0.208). Therefore, a reduced model was used giving a significant linear relationship where Droplet Density = 0.553·Vol_F (F=1134.45, df=1,79, P>F=<0.0001) (see Fig. 3). This result suggests that

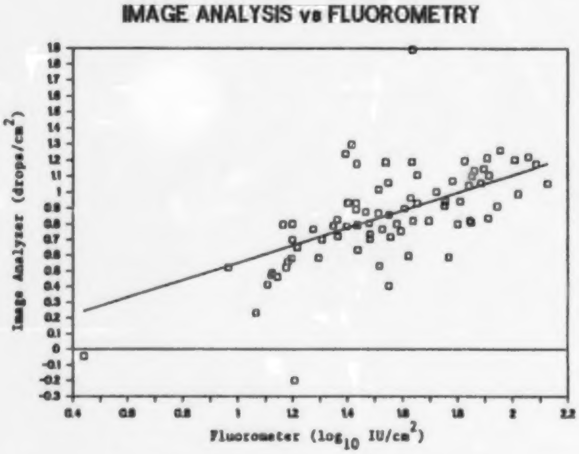

FIGURE 3: RELATIONSHIP BETWEEN DEPOSIT PER AREA (IU/cm^2) MEASURED BY FLUORESCENT ANALYSIS AND THE DROPLET DENSITY MEASURED AT SAME CANOPY LOCATIONS.

leaves had a similar spectrum of droplet sizes and that dose differences between leaves was due mainly to the number of droplets per unit area. However, it should be noted that this relationship was based on accurate image analysis which counted droplet stains down to a theoretical size limit of 36 μm. Since even these small droplets have been given equal weight in the estimation of droplet density, it seems that future use of this relationship will require accurate density measurement.

Comparison of percent area from image analysis with fluorometer volume resulted in a significant linear relationship % Area = -2.582 + 1.131 · Vol_F and an r^2 value of 63.9% (F=138.04, df=1,78, P > F=0.0001) as shown in Figure 4.

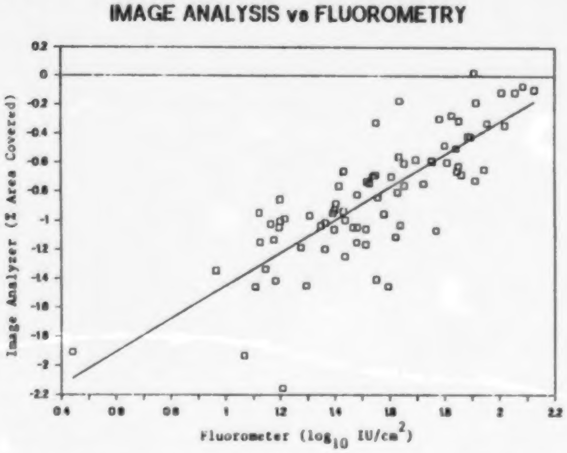

FIGURE 4: RELATIONSHIP BETWEEN DEPOSIT PER AREA (IU/cm^2) MEASURED BY FLUORESCENT ANALYSIS AND THE PERCENT OF LEAF AREA COVERED BY SPRAY MEASURED AT THE SAME CANOPY LOCATIONS.

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PREDICTION OF PEST MORTALITY FROM DROPLET MONITORING MEASUREMENTS DURING ULV APPLICATION

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ABSTRACT — An accurate estimate of likely pest mortality in ULV insecticide application is possible, provided that:
a) the mode of action is by direct contact,
b) the insect target is exposed to the drifting drops,
c) the vertical equivalent area and drop collection efficiency of the insect can be estimated,
d) the drop availability can be measured, and
e) laboratory bioassay can supply dose/mortality data.

For validation, the drop deposition on wild caught tsetse flies resulting from the application, over savannah woodland, of a non-toxic formulation containing a fluorescent tracer was measured by fluorimetric technique and compared with the deposit levels predicted from drop counts taken from magnesium oxide coated slides spun on rotary samplers. Good correlation was obtained between predicted and observed tracer dose when appropriate collection efficiency and sampling rate corrections had been made.

RÉSUMÉ — Une estimation précise de la mortalité probable des insectes nuisibles, par l'application d'insecticide à ultra bas volume, est possible, à condition que:
a) le mode d'action soit par contact direct,
b) l'insecte cible soit exposé aux goutelettes dérivantes,
c) l'emplacement équivalent vertical et l'efficacité du ramassage des goutelettes de l'insecte puissent être évalués,
d) la disponibilité des goutelettes puisse être mesurée, et
e) le laboratoire d'essai biologique puisse fournir les données sur la dose/la mortalité.

Pour la validation, après l'application dans la savane d'une formule non-toxique contenant un indicateur fluorescent des mesures de la déposition de goutelettes sur des mouches tsé-tsé sauvages capturées ont été faites par la technique fluorimétrique et ont été comparées aux niveaux de dépositions calculés à l'avance par le dénombrement des goutelettes sur des lames de verre recouvertes d'oxide de magnésium tournant sur des échantillons rotatifs. Lorsque les corrections nécessaires de l'efficacité du ramassage et la vélocité des échantillons ont été faites, une bonne corrélation a été obtenue entre les doses indicatrices prévues et celles observées.

INTRODUCTION

Prediction of pest mortality by means of drop monitoring measurements during application of the toxic chemical is dependent on recognition of the manner in which the pest can acquire a lethal dose. If the mechanism can be modelled, e.g., by quantitative interpretation of the physical and statistical processes involved, and if dose/mortality data derived from laboratory toxicological studies are available, then prediction of lethal effect becomes possible.

Where the mode of action is *indirect*, i.e., where the intention is to produce a residual foliar deposit from which insects may acquire a lethal dose by secondary contact (e.g., by alighting, or walking over the deposit), or alternatively by ingestion of the contaminated foliage, the model may be difficult to define with precision, but where the mode of action is by *direct* contact of small wind-borne drops onto the insect exposed in the airstream, the model becomes correspondingly simpler and can afford an accurate estimate of the likely effect.

The method to be described has been derived with particular reference to control of the African tsetse fly using the aerially-applied sequential aerosol technique (Allsopp, 1984) and represents a practical extension of the theoretical model previously reported (Johnstone, 1986a; Johnstone and Cooper, 1986) and subsequently validated by field experiment (Johnstone *et al.*, due Jan 1988).

PRINCIPLES

Very small drops, certainly those less than about 30 μm in diameter, having small fall velocities < about 0.03 m/s, are transported on air currents so that fallout occurs extremely slowly. Deposition takes place principally by inertial impaction on vertical surfaces in the path of the wind unless conditions are exceptionally calm. The same holds true for somewhat larger drops if the windspeed is large compared with the fall velocity, e.g., taking drops of 50 - 100 μm, in windspeeds ≥ 2.5 m/s (when the windspeed is ≥ 10× the fall velocity), the drops travel along the wind at only a shallow angle of fall.

Provided it is possible to measure the flux of drops across unit vertical area at points in the vegetation canopy where the pest is thought to rest, it becomes possible to estimate the amount of spray collected by a resting target insect, since this must depend essentially on the projected vertical area of the insect and the efficiency with which drops are collected on such an obstacle.

Accurate measurement of both flux of drops and the drop size spectrum requires care, as sampling devices, such as the cascade impactor (May, 1945) and the rotary slide sampler (Andrews *et al.*, 1983) are < 100% efficient in collecting very small drops. However, if the manner in which the collection efficiency of the sampler varies with drop size is known, it is possible to make correction for varying collection efficiency and, if the prevailing windspeed is also measured, a correction can be applied for any lack of isokineticity in the sampling rate (Johnstone, 1986b; Cooper *et al.*, 1987). When these corrections have been made, a good estimate can be achieved of the drop flux, both in terms of drop numbers and volume. In order to determine the mass flux it is necessary to know what the volume flux represents in terms of the corresponding volume on emission, since it is normal for at least a proportion of the carrier solvent to evaporate between emission and deposition (Jarman, 1958), and indeed in tsetse spraying the formulation is designed so that an initial drop size spectrum (vmd ≃ 75 μm) is reduced to the required size (vmd ≃ 20 μm) by evaporation, as direct atomisation to the smaller size has not proved possible. Provided the percentage evaporation is known (theoretically, or by prior, or simultaneous experiment), the measured volume can be increased by the appropriate evaporation factor, before using the initial insecticide concentration to derive the actual mass flux.

The mass flux through the projected vertical area of the target pest represents the expected deposition at 100% collection efficiency but, with very small drops and in light winds, the collection can be very low. Collection efficiency is essentially a function of drop size, windspeed and width and shape of the interposed obstacle and may be estimated using empirical impaction data for cylinders and ribbons, such as those supplied by May and Clifford (1967). For tsetse flies, recent laboratory wind tunnel tests have established the variation in average collection of resting flies over the drop size range 10 - 25 μm and wind speed range 0.25 - 1.5 m/s, with extrapolation to larger sizes and higher windspeeds. Thus with knowledge of the prevailing windspeed and a mean drop size derived from the corrected sampler data, an appropriate collection efficiency can be used to reduce the expected deposition to the appropriate value.

The final step involves comparison of the predicted dose with the appropriate laboratory determined dose/mortality relation to assess the most probable effect.

METHOD

Battery-operated rotary samplers bearing narrow glass slides (0.6 × 7.0 cm) coated with magnesium oxide, form the standard sampling tool for monitoring aerosol applications against tsetse flies (Andrews *et al.*, 1983; Cooper *et al.*, 1987). These are deployed on tripod stands and set at a height of about 1.25 m within the savannah woodland fly habitat where the spray cloud is to be monitored, together with an electrical cup anemometer to measure wind run. Both devices may be switched on and off, either manually, or by a pre-set electrical time switch. At the conclusion of sampling, the drops present on the slides are counted and sized with a low power microscope (×30 - ×60), crater diameter being converted to true drop diameter (May, 1950). A correction is made to the numbers in each size class based on the collection efficiency of the sampler for drops of each class mean size and the drop size parameters (nmd, vmd, and number and volume passing unit area) are then determined by a short computor programme. The volume per unit area is corrected for departure from isokinetic sampling by a correction factor which is dependent on geometry and speed of rotation of the sampler and is also proportional to the windspeed. The evaporation correction is best determined empirically, by preliminary experimental sampling using fluorescent tracer and plain glass slides (from which the tracer can be recovered and determined fluorimetrically), to provide a mass and volume estimate independant of evaporation. Comparison of this with the volume obtained by drop size count on a corresponding MgO coated slide provides an estimate of the evaporation related to the mean drop size on the slide. The volume/unit area, corrected for evaporation, provides an equivalent mass/unit area (where mass = concentration × volume). A resting tsetse fly has a projected vertical area of about 0.25 cm^2, so the deposit/fly, if all drops were to impinge, would be 0.25× mass/unit area. However, the collection efficiency of the fly will depend on wind speed and drop size in a manner which has been the subject of laboratory determination (Johnstone *et al.*, to be reported), see figure 1, so that, identifying the drop diameter with the vmd and the windspeed with that measured, a correction based on the graphically-derived collection efficiency can be made to give the most likely mass dose/fly (insecticide, or tracer, as appropriate). The predicted dose levels may be compared with laboratory dose/mortality data (Hadaway and Barlow, 1975).

A trial to validate this procedure was carried out in Zimbabwe in 1986 and a full report has been prepared (Johnstone *et al.*, due Jan 1988). The trial used a blank formulation mimicking a commercial endosulfan formulation (Thiodan 30% e.c.), but containing 0.4% fluorescent tracer (Hostalux KCB), which allowed a simultaneous calibration of the carrier evaporation taking place between emission and collection. Rotary slide samplers armed with MgO coated and plain glass slides were stationed across the spray block, and were operated during, and for two hours after, the spray operation. These were assessed microscopically (MgO) and by fluorimetry (plain glass). Wild tsetse flies (*G. morsitans*) were caught in the block prior to spraying, to provide a control blank, and again two hours after the spraying had been completed, for fluorimetric assessment of the tracer deposition.

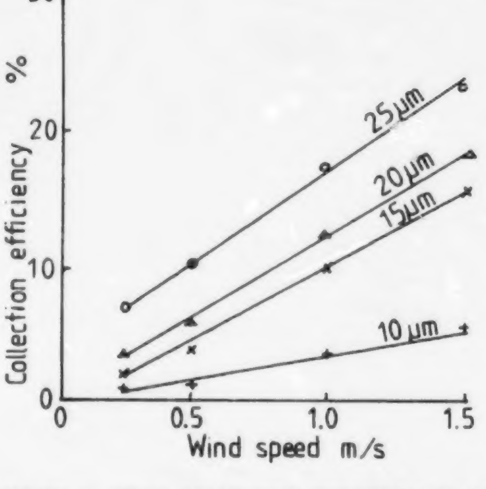

FIGURE 1: MEAN COLLECTION EFFICIENCY OF TSETSE FLIES AT REST ON SMALL CYLINDRICAL SUPPORTS (0.63 AND 2.5 cm IN DIAMETER).

RESULTS

Figure 2 shows the median tracer deposits found on batches of flies captured over several linear locations across the spray block, compared with the deposits predicted from drop size counts from the neighbouring monitoring slide samples, using the analysis outlined above. Equivalent endosulfan levels, assuming the toxicant had been present at 30% concentration, are also indicated, in relation to the LD50 and LD99.9 dose levels.

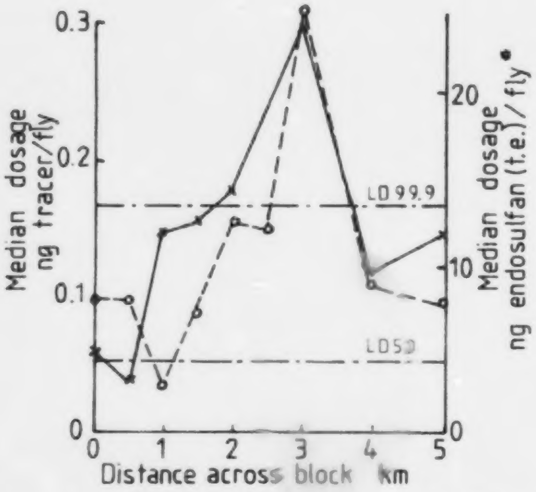

FIGURE 2: COMPARISON OF MEASURED AND PREDICTED DOSAGES/FLY AT VARIOUS POSITIONS ACROSS THE SPRAYBLOCK.

x————————x Predicted from rotary samplers

o– – – – – – –o Measured by direct fluorimetry (flies taken 2-4 hrs post spray)

* Tracer equivalent, assuming nil evaporation of endosulfan, sprayed at 30% a.i.

DISCUSSION

The correspondence between observed and predicted tracer dose is remarkably good and suggests the physical samplers can provide a very satisfactory indication of dose levels, which may then be used to estimate the likely control mortality. This quantitative biological interpretation greatly enhances the value of the physical sampler as a tool for routine monitoring of tsetse airspray control and possibly other related pest or vector control operations.

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MEASURING FOLIAR DEPOSITS FROM AERIAL SPRAYING OF PESTICIDES

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ABSTRACT — The measurement of foliar deposits in forests after experimental sprays presents many practical problems. A method based on the use of foliage simulators is described. The simulators were designed to mimic the collection efficiency of balsam fir shoots. The methods of deployment in the field and field calibration techniques are described. Some results from the 1986 Dunphy spray trials are presented to show comparison between TBM and CESSNA 188 applications.

RÉSUMÉ — La mesure des dépôts foliaires dans les forêts, après des traitements expérimentaux par pulvérisation, présente de nombreux problèmes pratiques. On décrit une méthode basée sur l'emploi de simulateurs de feuillage. Ces simulateurs ont été conçus de façon à posséder le même pouvoir collecteur que les pousses de sapin baumier. On décrit les méthodes de mise en place ainsi que les techniques d'étalonnage sur le terrain. On cite certains résultats obtenus au cours des essais de pulvérisation réalisés en 1986 à Dunphy pour comparer les traitements effectués avec un TBM et avec un CESSNA 188.

INTRODUCTION

One of the most demanding tests of the accuracy of aerial spraying experimentation in forest applications is closure of the mass balance. Obtaining representative samples of deposits on foliage and other elements of the forest and accurately measuring the drift of airborne droplets from the test site are the two major procedural problems. In this paper, a method for measuring foliar deposits which is economical, relies on no adjustable factors, and which has given reasonable closures will be described.

These procedures were developed for a series of large-scale spraying trials at Dunphy, N.B. by a number of agencies working under the guidance of the New Brunswick Spray Efficacy Research Group. Our group was given the responsibility of measuring deposits on foliage and ground. Since the test site was repeatedly sprayed with the same tracers, foliar deposits could only be estimated either by systematic placement of uncontaminated foliage samples over the test plot, or by the use of foliage simulators. The former procedure has the advantage that receptors are actual foliage, but the physical bulk of the samples presents difficulties in handling and analysis. The use of simulators avoids this problem, provided that a reliable calibration of the deposits on simulators vs foliage is available. Using the data available from work in this laboratory on collection efficiencies of coniferous foliage, and on the design of foliage simulators, a procedure could be developed.

EXPERIMENTAL METHODS

Overall Description of Methods

The test site was a forest consisting mainly of jackpine and black spruce. A single spray line was chosen and a sampling line approximately normal to it was established. Stand statistics were obtained by examining eleven 245 m^2 plots along the sampling line.

The ground and foliage deposits were to be measured to 1200 m downwind of the spray line with particular attention paid to the first 400 m. Spacing of measurement sites was 10 m in the first 100 m, with wider spacing further downwind. At each downwind distance, three sampling sites were located along an 80 m transect, parallel to the spray line. Average foliage deposits were estimated for each of these transects by a compositing procedure which will be described.

In these experiments, two different aircraft were used and each made five passes over a half-hour period. Each aircraft sprayed an emulsified organic mixture, one with a tracer of tris-2-ethylhexyl phosphate, the other triphenylphosphate.

At each site, foliage simulators were exposed during the test. They were attached to racks and hoisted to preselected heights on halyards attached to trees. Eighteen simulators were used per line and after exposure they were combined, and washed with a solvent which was analyzed for the two tracers.

Foliage Simulators

Foliage simulators (Fig. 1) were developed in this laboratory for this purpose. The simulators have been tested in a small wind tunnel and their collection efficiency measured for air velocities of 0.52 to 1.85 m/s and for droplet sizes ranging from 10 μm to 55 μm. Similar measurements have been made for shoots of balsam fir, red spruce, white spruce and jack pine. The simulators were designed to give collection efficiencies similar to those of balsam fir. Laboratory-derived collection efficiencies were not used in the field experiments, and a calibration was done as part of the spray trials.

Placement of Foliage Simulators

The simulators were exposed in sets of 18 per transect. At each site, six simulators were normally used. From the survey of stand characteristics the average cumulative foliage fraction vs height was determined. It was found that by placing two simulators each at 4, 8 and 12 m from the ground, each level of simulators could be considered representative of equal foliage areas.

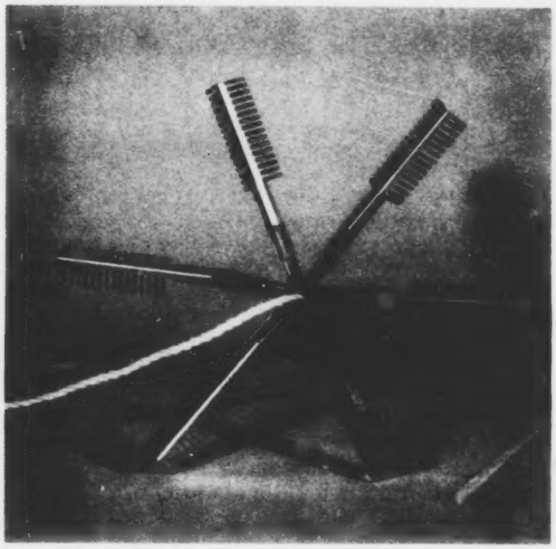

FIGURE 1: FOLIAGE SIMULATORS AND RACK.

The halyards were attached by rings as high as possible in the tallest tree close to the sampling site. Some trimming of the test tree was often necessary. The halyards were placed in most cases so that on each transect one was on the windward side of the tree, one downwind and one to the side.

The 18 simulators required for one transect were stored in a labelled Mason jar. Before the test, they were mounted on the racks and hoisted in place. After the trial, they were immediately returned to the Mason jar.

Calibration of the Foliage Simulators

Additional trees were fitted with halyards and racks for calibration purposes. Each rack held five simulators and a spray of uncontaminated foliage about 30 cm (1 ft.) long. Eighteen racks in total were used in each trial. Samples of balsam fir, jack pine and red/black spruce were exposed. The foliage samples were stored in plastic bags and, later, shoots were removed and the tracer contents analyzed.

The analyses were used to obtain the constant of proportionality in the relation deposit of tracer in μg per g of foliage = K_i × deposit in μg on a simulator

where K_i is species-dependent.

Calculating Foliage Deposits from Simulator Deposits

Deposits were calculated on the basis of a sq. m of ground and were normalized for source strength. The latter was defined as $S = g$ tracer released per m of flight path during the test and was obtained from the aircraft speed, application rate and tracer content of the mix.

Tree surveys of the test site gave the number of trees of each species per unit area for each 50 m segment of the sampling line. The diameters of the trunks at breast height (DBH) were also measured. A number of trees were cut down and the foliage removed and weighed to obtain relationships between weight and DBH for each species of interest. Foliage samples were also removed and the relationship between projected foliage area and weight (m^2/g) was determined for each species (f_i). By this procedure, the foliage area per sq. m of ground was obtained for each species (call F_i).

For a given transect, a weighted value of a term which described the relative efficiency of collection by foliage with respect to simulators was obtained as follows

$$E = \sum_i \left(\frac{K_i}{fi} \times (Fi/\sum_i Fi) \right)$$

The weighting is for the relative areas of foliage of different species.

If m is the deposit of tracer per simulator in μg, then the deposit of tracer in μg per g released per m^2 of foliage equals

$$\frac{mE}{S}$$

and the normalized deposit in $\mu g/g$ per m^2 of ground is

$$\frac{mE \times \Sigma F_i}{S}$$

Measuring Ground Deposits

Ground deposits were measured by placing 0.23 m^2 rectangular aluminum plates on the ground near each foliage-sampling site. The plates were washed with hexane and analyzed for the two tracers. The total deposits were corrected for source strength and relative areas to give the ground deposit in $\mu g/g$ released · m^2.

Analyses of Samples

Each set of 18 simulators was stored in a sealed jar and later washed with hexane. The extract was concentrated to 5 mL 100 mL of technical grade in a rotary evaporator, then analyzed for the two tracers by gas chromatograph.

Mass Balances

The foliage and ground deposits are expressed in terms of $\mu g/m^2$ of ground per g tracer released per m of flight path. It is therefore convenient to write a mass balance for a one metre wide strip normal to the flight line. Deposits can be numerically integrated over the downwind direction as far as the sampling grid extends (as shown in part on Table 1). In the case of these experiments, foliar and ground deposits were integrated to 400 m, where drift measurements were also made. The mass balance could then be closed to 400 m downwind.

EXPERIMENTAL RESULTS

Calibration of Simulators

The constant of proportionality, K_i, was obtained for balsam fir, black spruce and jack pine. The results are shown in Table 2. Experimental data for jack pine are shown on Figure 2. The constants were obtained by linear regression through the origin. Since two aircraft were used with different tracers, two correlations were possible for each species. No systematic differences between results for the two tracers were found. There were differences in the droplet spectra of the emitted spray and in the distribution of foliar deposits for the two cases, which suggests that the method is not sensitive to small changes in droplet size and wind speed.

TABLE 1: Typical Calculations of Foliar Deposit

Transect (m from spray line)	ΣF_i m^2/m^2	E	mx18 (µg per 18 simulators)	Deposit (µg/m²)	ΔX m	Integral Value (µg/g released)
20	2.64	285	0.117	5.3	20	106
30	2.64	285	0.273	12.3	10	123
40	2.64	285	0.136	6.13	10	61
50	2.99	302	1.62	72.9	10	739
60	2.99	302	3.07	167	10	1670
70	2.99	302	3.56	192	10	1920
80	2.99	302	7.30	395	10	3950
90	2.99	302	6.58	356	10	3560
100	3.11	313	11.09	575	5	2875

Fractional Deposit on Foliage to 100 m = 0.015

Source strength S = 0.923 g/m of flight path

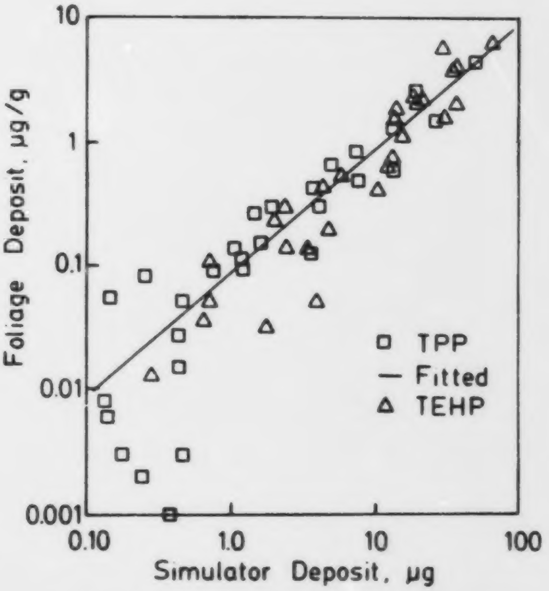

FIGURE 2: FOLIAGE DEPOSIT PER g OF JACK PINE SHOOT VS. DEPOSIT PER SIMULATOR.

TABLE 2: Calibration of Foliage Simulators

	K_i		
	Fir	Spruce	Jack Pine
TPP	0.590±0.034*	0.542±0.034	0.432±0.022
TEHP	0.750±0.046	0.492±0.046	0.486±0.033
n	29	29	29
Average	0.665	0.517	0.459

K_i is expressed in µg tracer per g foliage/µg tracer per simulator.

* standard error of the slope of the regressed line.

Foliage and Ground Deposits - Typical Measurements

Results from one of the tests done at the Dunphy spray trials of 1986 will be described. Two aircraft were used, a Grumman TBM fitted with 24 Teejet 11010 hydraulic nozzles and a Cessna 188 (Ag Truck) with four Micronair AU4000 rotary atomizers. Both aircraft sprayed an emulsion designed to simulate the fenitrothion emulsion used in operational spraying. The AU4000 settings were adjusted so that its emitted droplet spectrum was similar to that of the spray generated by the TBM. Droplets from each aircraft were marked by different chemical tracers and dyes.

The aircraft each made five passes at average heights above ground of 40 (TBM) and 35 m (AgTruck). The test was started at 2100 hrs under stable conditions. Wind speed at aircraft height was 3.5 m/s.

Mass balances for the two aircraft are shown on Table 3. Deposits are plotted against downwind distance on Figure 3. The closure of the two balances shown is better than usual in this set of nine trials (average recovery of tracer was 83%; range 53-113%).

Although the estimates of foliage and ground deposits may be subject to consistent errors, in relative terms it is clear that the larger aircraft is the more successful in depositing insecticide on foliage in the first 200 m. Although the larger aircraft flew higher, its trailing vortex system is the more powerful and it pushed the droplet cloud into the forest canopy more effectively. Farther downwind, the deposits from the two aircraft are much the same, suggesting that the vortex effect is largely lost.

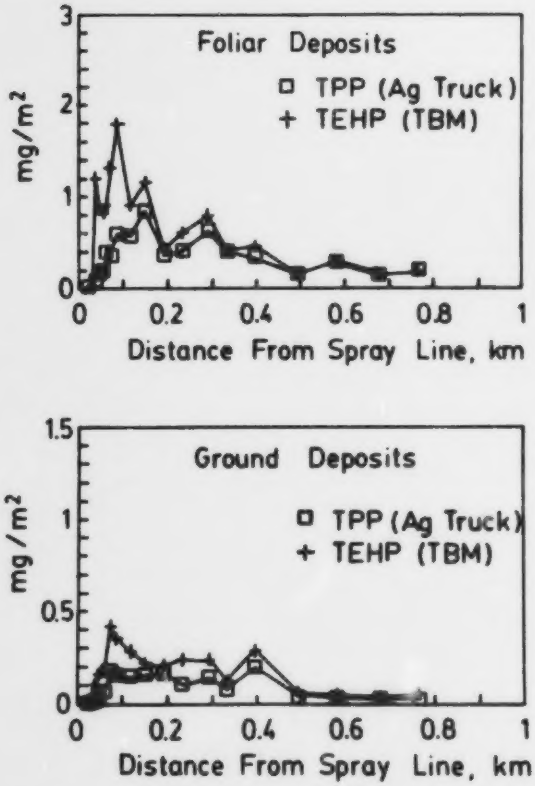

FIGURE 3: FOLIAR AND GROUND DEPOSITS VS. DISTANCE FROM SPRAYLINE. BASIS: 1 g. TRACER RELEASED PER m OF SPRAY LINE.

TABLE 3: Mass Balances for One Spray Test

	Fractional Deposits			
	TBM		AgTruck	
	to 400 m	to 760 m	to 400 m	to 760 m
Canopy	0.310	0.383	0.190	0.261
ground	0.099	0.119	0.058	0.071
drift (measured)	0.538		0.743	
unaccounted for	0.053		0.009	

DISCUSSION OF RESULTS

Calibration of Simulators

The results for jack pine (Fig. 2) were plotted using logarithmic scales because of the wide range of the chemical analyses found. The scatter on the left side of the plot can be partly attributed to contamination of simulators and/or foliage while deploying and recovering them. The scatter at higher concentrations arises from the inhomogeneities of the spray cloud which are not wholly averaged by the five passes by the aircraft and the use of five simulators per test point. Earlier measurements have shown that deposits on simulators exposed 10 cm apart can vary widely.

The collection efficiencies of simulators and foliage attributable to inertial impaction have been measured in wind tunnel tests in our laboratory. Estimates have been made of the term K_i from these measurements and it has been found that generally they are about four times those observed in the field. The calculation is necessarily approximate because of difficulties in handling orientation of the collectors, the effect of droplet size and the contribution of gravitational settling. The field calibration gives the more reliable results.

The procedure used to estimate foliar deposits from measurements obtained from the sets of 18 simulators is based on the assumption that a typical shoot on a tree receives, on the average, the same deposit as a shoot exposed in the calibration procedure. This assumption may not be correct because of at least two sheltering effects. It is well known that the upwind side of tree is likely to have greater deposits than the downwind side. It is also reasonable to expect that a shoot on a single spray, held on a rack as in the calibration procedure, is less sheltered from the droplet cloud than many shoots on a full branch.

In the first case, the halyards holding the simulators were placed in different positions to avoid systematic errors caused by the sheltering effect of the tree. The second cause of error cannot be avoided and will bring about an overestimate of foliage deposits using these methods.

Ground Deposits

The method used to determine ground deposits is based on the assumption that any droplets which penetrate below the canopy are collected primarily by gravitational settling. Wind speed is much lower than at canopy level. At this test site much of the ground is covered with small plants of various species which provide much surface area for collection of droplets. The deposit plates were placed in areas cleared of these small plants and it was assumed that droplet flux to a plate was typical of adjacent areas.

There is no straight-forward method to analyze systematic errors in this procedure.

Closures of the Material Balance

Error in closing the material balance will also arise because non-foliage elements of the trees are not allowed for in the calculation. Branches, stems, bark, etc. will collect tracer but it is difficult to estimate the relative contribution of such collecting surfaces. Also neglected are trees of species present in small numbers and other plants. These factors lead to underestimates of deposits.

It is reasonable to expect that any systematic errors in measuring foliage and ground deposits are much the same for each trial in the set. The results for eight sprays were examined to determine whether or not a correction factor applied to the foliage and ground deposit estimates would improve the closure of the balances. When percent closure is plotted against foliar deposit, however, the points are randomly scattered. If departures from perfect closure are primarily caused by systematic errors in the estimates of foliar deposits, a statistically significant relation would emerge.

Droplet Spectra

The foliage simulators are designed to collect droplets with approximately the same efficiency as balsam fir shoots. At Stokes numbers based on needle width less than about 0.2, the efficiency of collection by either fir shoots or simulators is less than 10%. Wind speeds in the canopy were of the order of 1 m/s or more, at which speed the Stokes number is about 0.2 for 10 μm droplets. Hence, most of the large number of droplets smaller than 20 μm released from the aircraft are not expected to report to the simulators.

During these trials, droplet spectra were obtained from simulators and Rotorods which had Kromekote paper attached to the collecting surfaces. The droplets captured were sized microscopically. The simulators were exposed between 60 and

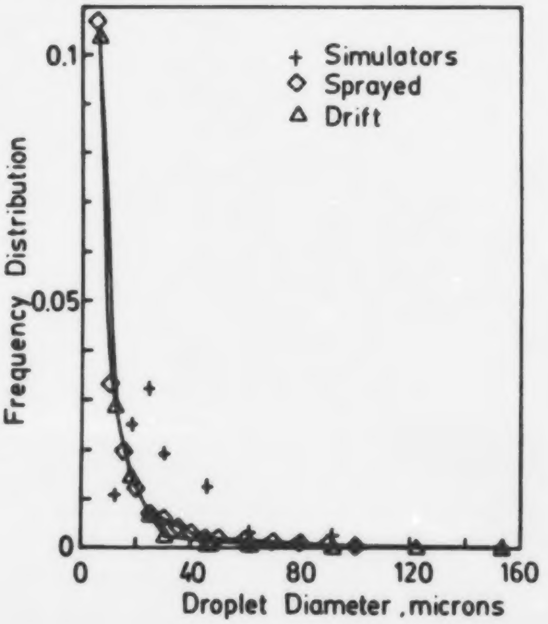

FIGURE 4: NUMBER FREQUENCY DISTRIBUTIONS FOR DEPOSITS ON SIMULATORS, EMITTED SPRAY AND DRIFT CLOUD AT 400 m.

100 m from the spray line in the same way as the others. The Rotorods sampled the drift cloud at 400 m. On Figure 4 the number distribution of the emitted spray from the TBM is compared with those of the drift cloud and deposits on simulators. The plot shows clearly that the simulators collect few droplets smaller than 10 μm and that the drift cloud has been winnowed of larger droplets.

The foliage may be a more efficient collector of sub-15 μm droplets than simulators because of its relatively rough surfaces. This plot shows that because the volume fraction smaller than 15 μm in the evaporated spray is less than 15%, differences in collection efficiency are of minor significance.

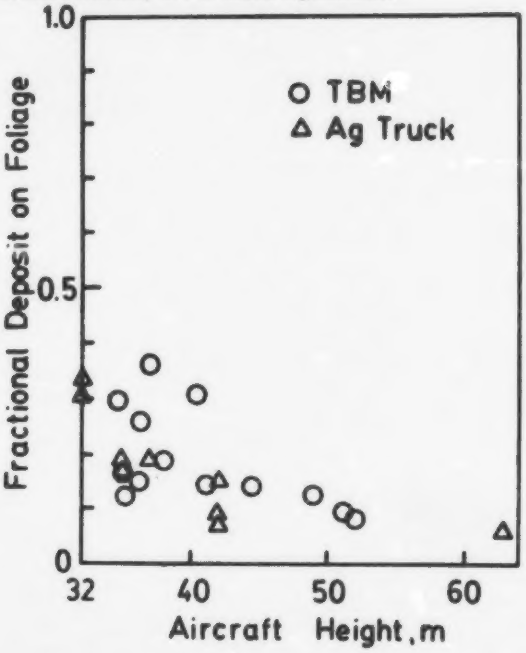

FIGURE 5: FOLIAR DEPOSITS VS. AIRCRAFT HEIGHT.

Comparison of Deposits from the Two Aircraft

One of the purposes of the 1986 Dunphy trials was to compare the deposits from two aircraft commonly used in operational spraying. The results obtained demonstrate the usefulness of this technique for measuring foliar deposits.

The TBM normally sprays swaths of 132 m width so that with normal overlapping from cross wind spraying, the foliar deposit to 400 m is a useful criterion to use in this comparison. Sensitivities to atmospheric stability, wind speed and aircraft height were examined for both aircraft. No systematic dependence on stability or wind speed was observed but the height of the aircraft above ground level proved to a significant influence on foliar deposit. These results shown in Figure 5, also show that over nine trials with wind speeds at aircraft level varying from 1.7 to 6.6 m/s and stability from unstable to highly stable, the TBM gave higher foliar deposits, particularly when flown at less than 40 m above ground level.

CONCLUSIONS

The method described here for measuring foliage deposits in forest-spraying experiments relies on

a. detailed measurements of the characteristics of the forest of the experimental site,

b. on the use of foliage simulators placed at levels consistent with the average vertical distribution of foliage area in the forest, and

c. on a simultaneous calibration of simulators against foliage samples.

Measurements of foliar and ground deposits taken in eight field trials, when combined with drift measurements, have accounted for 83% of the tracer released. Discrepancies in the balance arise from errors in deposit measurements but cannot be accounted for by a fixed correction factor applied to them, which suggests that random errors in the drift measurements are at least as important.

This technique could be further refined by additional experimentation to determine the deposits on non-foliar collection surfaces and verification of the measurement technique for ground deposit.

ACKNOWLEDGEMENTS

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SPRUCE BUDWORM MOTH FLIGHT: POSSIBLE IMPLICATIONS OF FIELD RESEARCH FINDINGS FOR POPULATION DYNAMICS AND MANAGEMENT

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ABSTRACT — Work at UNB showed that spruce budworm moths fly much higher, particularly in rain, and for longer — and therefore much further, than first reported. The potential of moths migrating from afar, being reconcentrated by winds and starting new outbreaks is discussed and could be tested against budworm history. Implications for monitoring and management are suggested.

RÉSUMÉ — Le travail à l'UNB a démontré que les ailés de la tordeuse des bourgeons de l'épinette volent, surtout dans des conditions pluvieuses, plus haut ainsi que plus longtemps, se déplaçant, donc, plus loin, qu'il a été signalé au début. Le potentiel du départ des invasions, par reconcentration sous l'effet des vents des papillons venant des sources lointaines, est discuté. Ces conclusions sont vérifiables contre l'historique connu de la tordeuse. Quelques propos sont avancés sur les implications pour la surveillance et la lutte intégrée.

Initial results of studies in New Brunswick on four seasons of spruce budworm moth flight (1973-76), using radar and aircraft, were reported by Greenbank, et al. (1980). Further data from that program were analysed at UNB and published in the meteorological literature (Dickison, et al, 1983, 1986). The results confirmed early observations (e.g. Henson, 1951; Wellington, 1954; Greenbank, 1957) associating mass moth arrivals with thunderstorms and cold fronts, but extended the association to include warm frontal conditions and also clear weather conditions in which wind convergence occurs on sub-synoptic scales, as with the development of a marine flow or sea breeze. Moreover, the sampling methods used enabled the density and displacement of airborne moths to be quantified. The findings could help to resolve what has been indicated as a key problem in current population and ecosystem ecology, in particular for spruce budworm — the lack of an effective method of data analysis (Royama, 1981).

EQUIPMENT AND METHODS

The equipment and methods used in the 1973-76 field studies are detailed in Greenbank, et al. (1980). The 3 cm wavelength ground-based marine radars were found capable of detecting single budworm moths at ranges of 500-1300 m and low-flying concentrations of moths at 30 km. One such radar was sited in a forest clearing at Chipman in south-central New Brunswick in 1973-75 and at Acadia in 1976, with a second, similar radar set at Renous, some 100 km further north, in 1974 and at Juniper, about 100 km north-west of Chipman, in 1975. From each base, Cessna 185 light aircraft with insect collecting nets (Spillman, 1980) were flown under radar guidance to sample the airborne insects present. Meteorological observations were made at each radar site, with local upper winds determined by pilot balloons. In order to put these observations into the context of the changing winds and weather systems of New Brunswick, a DC-3 aircraft, equipped with a Doppler navigation system that could measure wind speed and direction within an accuracy of a few knots, was flown around the province each evening during the period of main moth flight activity. From 1974 onwards, the DC-3 also carried insect collecting nets, weather radar and a fuller range of equipment for measuring temperatures and turbulence. By 1976, downward looking airborne radar systems had been developed that could detect individual moths down to the canopy from an aircraft altitude of 750 m. Sets were installed in a Piper Aztec and in the DC-3, to measure moth densities at 32 levels below the aircraft at intervals of 10 m along the track; records were stored on tape.

EXAMPLES OF MAJOR BUDWORM MOTH FLIGHTS

The results of these field programs provided unique evidence of the effects of a range of different weather systems on the flight and distribution of the moths. The key finding was the repeated demonstration that in severely disturbed weather, moth flight occurred at substantially greater scales than in the fair weather of the studies initially reported, and that it was associated not only with cold frontal and thunderstorm conditions but also with warm-sector weather. With all of these there is heavy precipitation, implying vigorous wind convergence. In all these conditions there was evidence of important spatial redistribution of moth populations, to an extent likely often to swamp effects of locally produced changes in pest numbers.

Case studies of major flights by spruce budworm moths in disturbed weather — at an active cold front, close to active thunderstorms, and among widespread warm-sector rainstorms — were presented in detail by Dickison, et al. (1983, 1986). Cases of moths observed at high density, particularly in sea breeze fronts, are already on record (Rainey, 1976; Schaefer, 1976, 1979; Greenbank et al, 1980).

From the second year of field work, in-flight winds were mapped regularly in the DC-3, so that, when appropriate, the flight plan could be modified to obtain a quantitative assessment of the intensity of convergence across a windshift. Thus on 12 July 1974, it was possible near Bathurst to identify and explore a minor front (Fig. 1) not revealed by routine synoptic analysis, but which

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indicated a marine airflow penetrating deeply into the province. It was marked by a very sharply defined windshift, with the main transition zone no more than 300 m wide (Rainey, 1976). This was associated with active wind convergence, which was measured over a 90-sq. km quadrilateral of the aircraft's flight pattern (Fig. 14 in Greenbank, et al, 1980). The convergence found would have concentrated moths within the main transition zone at rates giving something like ten-fold increases per hour in the area-densities of the flying moths. At Chipman later that night, a radar line-echo was recognised independently, from its location and alignment most probably corresponding with a neighbouring section of the same front, and confirmed by aircraft trapping by the local Cessna as being due to budworm moths at high density. If this concentration of moths is envisaged as having settled later in the night not far from the line of the front as found from the DC-3 and seen on the radar, it would account for specially high kills (up to 60 moths per square metre) which were recorded in this particular area following experimental aircraft spraying operations against settled moths next day (R.J.V. Joyce, pers. comm.).

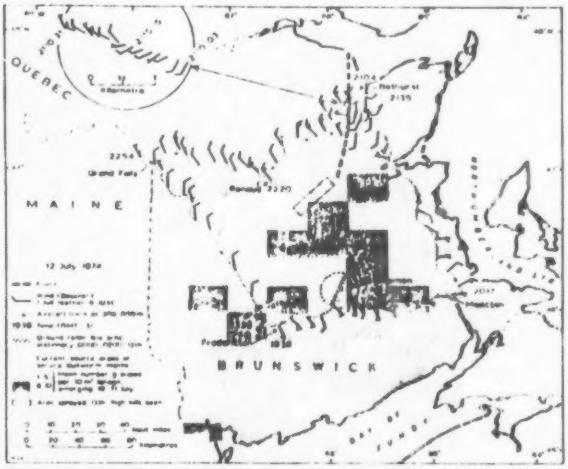

FIGURE 1: SPRUCE BUDWORM MOTH CONCENTRATION IN A ZONE OF WIND CONVERGENCE: INTEGRATED FINDINGS FROM SPECIALLY INSTRUMENTED AIRCRAFT, GROUND-BASED RADAR, PROVINCE-WIDE FIELD SURVEY, AND ASSESSMENT OF LARGESCALE SPRAY TRIALS (FROM RAINEY, 1978).

On 10 July 1976 a sea breeze front from the Bay of Fundy penetrated inland to beyond Fredericton; its passage was traced across an array of meteorological ground stations, and by the Acadia ground-based radar as a line echo of budworm moths taking off from unsprayed areas in the south of the province. The moth concentration in the front showed particularly clearly on the airborne radars in the Aztec and the DC-3; the latter had chanced to climb directly through the front and obtained a striking set of records of temperature, humidity, turbulence and winds, all of which changed synchronously. Full descriptions are given by Schaefer (1979) and Greenbank, et al. (1980). Even on this small scale of wind convergence passing over an area only 40 minutes after moth take-off began, the aerial density of moths in a 4 km band at the leading edge of the front was already ten times greater than in the air ahead of the front, up to a height of 500 m above ground.

Circumstantial evidence suggesting marked reconcentration of moths at substantial distances from their source areas was recorded early in the radar studies, and drew attention to probable links between spruce budworm outbreaks in Newfoundland and on the mainland -- consistent with later evidence from Dobesberger et al. (1983). On 8-9 July 1973, moths in very large numbers in fact appeared simultaneously in two widely separated regions under the influence of the corresponding sections of a single frontal system that stretched across both regions (Fig. 2). On the evening of the 8th, the radar at Chipman showed budworm moths at high density, flying at high level towards ENE with groundspeeds of about 65 km/hr and for an extended period. The next day (9th), spruce budworm moths, live and dead, were found in large numbers on the beaches at Shallow Bay in south-western Newfoundland, 450 km from the nearest of the budworm populations in New Brunswick and Gaspé.

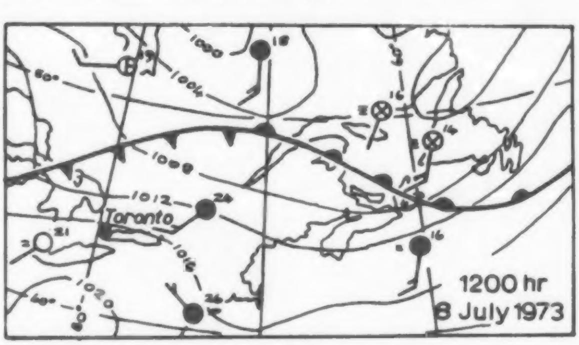

FIGURE 2: WEATHER SYSTEMS AT TIME OF MOTH RECONCENTRATIONS SEEN IN TORONTO AND NEWFOUNDLAND (ACKNOWLEDGEMENTS TO THE BRITISH METEOROLOGICAL OFFICE).

Synoptic charts for the period showed not only westerly winds extending to Newfoundland by dawn but also an eastward-moving warm front across the Gulf of St. Lawrence. The leading edge of these westerlies would have been an appropriate system of wind convergence to reconcentrate the moths, given the reduction in density to be expected in transit. This warm front, aligned NW/SE, was continuous with a cold front across Quebec and southern Ontario which advanced southeastwards over Toronto at about midnight on 8/9th. This cold front is likely to have been involved in the transport and reconcentration of the budworm moths which were flying in large numbers over the city on the morning of the 9th, around the meteorological office at the airport, seen at a 38th floor window by a provincial forest management entomologist (K. Turner, pers. comm.), and reported in millions from a traffic-monitoring helicopter.

MOTH FLIGHT AND WINDS

The radar studies repeatedly showed that budworm moths were transported with the wind. It was found (Greenbank et al, 1980) that the airspeed at which they fly is about 7 km/hr, substantially less than the windspeeds which they regularly encounter, and that the common orientation which they usually exhibit is very predominantly downwind. The displacement of the flying moths, relative to the ground, can accordingly be expected to be in the general direction of the wind in which they fly and often at a somewhat greater speed than the wind.

Long-range moth flights in steady winds may often involve marked reduction in the area-density of those moths. In radar observations on the dispersal of African armyworm moths, *Spodoptera exempta* (Walk.), from one particular outbreak, a ten-fold reduction in aerial density was measured over a distance of only 14 km (Riley et al, 1983). As these authors emphasise, some process for reconcentrating such moths must therefore be necessary if long distance flight is to result in new outbreaks. Light trapping and weather data have shown that *S. exempta* moths are caught in highest numbers on nights and indeed hours with windshifts associated with meso-scale or synoptic-scale wind convergence (e.g. Brown, et al, 1969; Haggis, 1971), and that the moths can be sufficiently concentrated to produce substantial new outbreaks some 150-200 km from the nearest known active sources of moths at the time (Haggis, 1979). Particularly high rates of concentration of armyworm moths were recorded by radar at the windshift at a storm outflow in Kenya (Pedgley, et al, 1982).

'Convergence' in a wind system means that the winds occurring at one time around the perimeter of an area give a net inflow of air. This may be due to the winds blowing in from two or more different directions, or to the wind speed slackening downstream in a windfield of uniform direction (the 'traffic jam' situation). An example of the former, measured by the Doppler equipped aircraft, is quoted above for 12 July 1974. Other examples are given by Rainey (1972, 1974, 1976) and Haggis (1979).

'Meso-scale' refers to atmospheric phenomena occurring on scales of tens to thousands of square kilometres, over which convergence can be much more intense than over the larger areas or synoptic scales of weather charts. Meso-scale convergence often occurs as localised, more intense areas within much more extensive areas of less vigorous overall convergence on the synoptic scale; the frontal system of 8-9 July 1973 is likely to have been such a case. At low levels (within 1-2 km of the ground), wind convergence necessarily involves ascent of air.

The net overall effect on airborne objects like moths travelling with the wind will be that they move towards and with zones of wind convergence. Within these zones they will tend to be carried up by the ascending air. In several different types of wind system involving vigorous meso-scale convergence, spruce budworm moths have in fact been recorded in numbers at heights around 1000 m, compared with the few hundred metres typical of more settled conditions. However, while the air commonly ascends to much greater heights than this in convergent wind systems, active flight by the moths is limited by low temperature. Budworm moths have not been seen taking off at temperatures below 14.4°C (Greenbank, et al, 1980), closely consistent with the lowest temperatures at which moths were caught in the DC-3 net, of 13.6° at 765 m and 13.8° at 910 m.

As the moths reach higher altitudes and lower temperatures (rising unsaturated air cools at a rate of 1°C/100 m), their flight muscles can no longer provide sufficient power for sustained flight, and the topmost moths will begin to fall relative to the surrounding air. As long as other moths continue to arrive at lower levels with the converging winds, moth concentration will occur, and moth numbers increase per unit volume as well as per unit of plan area. With appropriate wind observations, the rate of convergence can be estimated (e.g. 12 July 1974 above) and hence the rate of moth concentration to be expected.

The 1973-76 field studies on budworm moth flight provided repeated evidence of the process of moth concentration by wind convergence and of the particular types of weather systems involved. Moreover, these studies included an impressive demonstration, at Juniper in 1975, of moth immigration and subsequent egglaying at densities that completely swamped local effects of spraying to extinction the parent generation in a test block (Miller, et al, 1978); there was evidence that much of this moth concentration was associated with thunderstorms at a cold front (Dickison, et al, 1983).

GENERATION OF OUTBREAKS: A NEW HYPOTHESIS

By 1979, work on the budworm/forest simulation model had directed attention to an inescapable need for new hypotheses (Clark, 1979), and attention has recently been further directed (Royama, 1984) to evidence against the existence of the stable levels of low density endemic populations previously postulated. In view both of the substantially increased scales of budworm moth flight found by radar and aircraft, and of the mechanism and importance of moth concentration by wind convergence, we now offer a new hypothesis.

We suggest that the establishment of new outbreaks of spruce budworm, and the extension of existing outbreaks, may both occur as a result of immigration of moths, transported with the wind and concentrated by wind convergence, without necessarily involving any prior build-up or even existence of local low density populations. Rather, the sites of new areas of outbreak may be determined by the incidence and location of appropriate wind convergence at times of major moth flight. This probably occurs on only a few of the nights of moth flight each season. The 50% or so of egglaying which occurs before the females emigrate is envisaged as maintaining existing outbreaks while local forest conditions remain favourable for budworm.

Clark (1979) pointed out that well marked features of budworm history which remained unexplained by earlier hypotheses included the near absence, during 1958-65, of spread from the infestations of central New Brunswick into neighbouring peripheral areas of forest. These areas had been assessed as susceptible both by experienced local forest entomologists and by the model, and there was continued immigration into these peripheral areas by at least limited numbers of egg-carrying moths, as shown by light traps. It is now suggested that most of the emigrant moths from the existing infestations are likely to have overflown these peripheral areas and subsequently to have settled at greater distances, albeit at low densities unless they encountered convergent winds. The lack of consistent evidence of progressive spread from a number of uncontrolled individual outbreaks in Ontario and Quebec may be similarly explained, with 'progressive spread' now envisaged as requiring moth concentration by wind convergence in areas immediately adjacent to the existing outbreak. On the management problems of when and where the next new outbreaks may occur, the new hypothesis draws attention first to emigration from current outbreaks (even those at distances up to many hundreds of kilometres), and then to the particular areas of meso-scale convergence that develop on relatively few nights of major moth flight each season — rather than to low density populations.

MAPS FOR DATA ANALYSIS

Maps provide a system for presenting basic spatial data objectively and comprehensively, either to show the distribution of a subject, e.g. the areas of severe budworm infestation and defoliation in eastern North America each year (Kettela, 1982) — when all other subjects are omitted, or as a working tool for the analyst — when all related information is included. For analysis of the vast collection of data on the changing distribution of Desert Locusts, it was found most enlightening to borrow and apply the methods of the meteorological forecast office, where the three-hourly observations from weather stations worldwide are plotted on synoptic charts (or maps), with observations for different levels plotted on overlays. Only when the locust records were mapped on similar space and time resolutions to the wind data, and the two compared, could the complexities of swarm migration be unravelled and hypotheses fully tested (Rainey, 1963). The performance of the forecasting service improved commensurately when these methods were used operationally (Ministry of Overseas Development, 1965).

It is suggested that, for spruce budworm too, the method of data analysis that is still missing must now necessarily involve not only explicit treatment of real data on the changing spatial distributions of budworm populations (e.g. in Sippell, 1984), but also the contemporary synoptic data. This would mean intensified mapping for each season of moth flight, at appropriate scales of temporal and spatial resolution. For example, daily maps of all available trap counts (light and pheromone) and areas of contemporary moth emergence (from larval and pupal sampling), over much and sometimes all of the distribution area of the species, could be compared with the daily synoptic charts to identify both moth sources and sinks and the corresponding meteorological transfer processes (analogous to the procedure developed for the elucidation and forecasting of locust migrations). By retrospectively relating such maps to the relevant weather charts, our hypothesis on the generation of new spruce budworm outbreaks could be tested against the historical record.

A partial example of such a system is given in Figure 1, which also summarises the detailed evidence available on the source areas of the moths in the airborne concentration. This was provided by the routine survey counts at a thousand sampling points in New Brunswick; the counts, weighted by the area of susceptible forest within each 200 sq. km unit, utilised the emergence data of that season for each of the seven phenological zones covering the province.

IMPLICATIONS FOR MANAGEMENT

New options are now suggested for direct application in monitoring and for longer-term consideration in population studies and management, and that also have direct relevance for major pest problems in Africa and elsewhere. Current phenology, sampling and synoptic data, routinely available, could already make possible monitoring for long-range displacements of spruce budworm moth populations. The findings and methods outlined above suggest the basis of a system capable in principle of indicating not only when, but where new budworm outbreaks are to be expected.

For monitoring, an important further option is provided by the airborne insect-detecting radar, incidentally tested in 1987 by USDA for monitoring invading airborne insects coming into Texas. During 1986, international campaigns were launched against swarming grasshoppers and locusts in Africa, using spray aircraft from several different countries. A major problem encountered was of locating and selecting appropriate targets. Flying swarms had earlier been found particularly efficient targets for ultra-low-volume aircraft spraying (Rainey, 1963, 1972), and the feasibility of using aircraft fitted with wind-finding equipment and search radar for locating air-to-air spray targets has been studied by Joyce (1968), Rainey (1972) and Greenbank, et al. (1980). The airborne insect-detecting radar promises the final element of such a 'search and strike' system for methodically seeking, locating, assessing and controlling the airborne pest populations threatening new outbreaks of such major pests.

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DOSE TRANSFER AND SPRUCE BUDWORM BEHAVIOUR DURING OPERATIONAL APPLICATION OF FENITROTHION

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ABSTRACT – Spruce budworm larvae at the time of operational spraying with fenitrothion, confine themselves to and feed within the webbed area of their microhabitat. They are mostly in late third to early fifth instars and seldom crawl on the previous year's needles of balsam fir. The present best measure of effective spray deposit is 0.5 - 1 drop of fenitrothion >15 μm in size per previous year's needle. This amount correlates highly with effective foliage protection and insect mortality. However, it is an indirect measure of efficacy because most larvae do not live or feed on previous year's needles of balsam fir during spray operations. It is better than measuring droplets on Kromekote® cards or needle simulators for correlation of effectiveness. But, it cannot be related to the types and numbers of droplets going into the larval microhabitat, i.e., the webbed area where the budworm larva confines its activity during operational spraying. It is hypothesized that efficacy of sprays could be increased if droplets were targeted to the webbing and current foliage.

RÉSUMÉ – Au moment du traitement opérationnel au fénitrothion, les larves de tordeuse des bourgeons de l'épinette se réfugient et se nourrissent dans le réseau de fils de soie de leur microhabitat. Elles sont pour la plupart entre la fin du troisième stade et le début du cinquième et rampent rarement sur les aiguilles de sapin baumier de l'année précédente. Actuellement, la meilleure mesure d'un dépôt pulvérisé efficace est de 0,5 - 1 gouttelette de fénitrothion de plus de 15 μm par aiguille de l'année précédente. Il y a une corrélation étroite entre cette quantité et la protection efficace du feuillage et un taux de mortalité élevé chez les insectes. Toutefois, il s'agit d'une mesure indirecte de l'efficacité, parce que, pendant les opérations de pulvérisation, la plupart des larves ne vivent pas sur les aiguilles de sapin baumier de l'année précédente et ne s'en nourrissent pas. Elle est préférable à la mesure des gouttelettes sur des cartes Kromekote™ ou sur des simulateurs d'aiguilles pour ce qui est de la corrélation avec l'efficacité du traitement. Cependant, cette mesure ne peut pas être mise en relation avec le type et le nombre de gouttelettes qui pénètrent dans le microhabitat larvaire, c'est-à-dire dans le réseau de fils de soie dans lequel les larves de tordeuse se réfugient pendant la pulvérisation opérationnelle. On avance l'hypothèse selon laquelle l'efficacité des pulvérisations pourrait être augmentée si les gouttelettes visaient le réseau de fils de soie et les aiguilles de l'année.

INTRODUCTION

Aerial application of insecticides against forest insects is a well established pest management practice in Canada (Prebble 1975). Several insecticides have been registered and applied aerially against the spruce budworm, *Choristoneura fumiferana* (Clem.), based on empirical laboratory and field tests (Randall 1969, 1976; Nigam 1971, 1975; Dimond and Morris 1984; Shea and Nigam 1984).

In recent years, the number of insecticides available for operational use has decreased because of low industrial incentive to develop new insecticides, as a result of high development costs and stringent requirements of environmental safety by registering agencies (Metcalf 1980; Helson 1985; Nigam 1985). Only two insecticides, fenitrothion and *Bacillus thuringiensis* (*B.t.*) will be available for use against spruce budworm during the late 1980s because manufacture and testing of other suitable compounds, e.g., aminocarb and mexacarbate, are curtailed.

To make best use of available insecticides, studies to improve the effectiveness of fenitrothion were started under the auspicies of the New Brunswick Spray Efficacy Research Group (NB SERG) during the early 1980s (Varty and Godin 1983; Varty and Nigam 1985). The effectiveness of aerial application of an insecticide against spruce budworm is expressed in terms of percentage of foliage protected and larval mortality, which are functions of droplet density and size on the primary target surface on or near the larvae. The concentration of insecticide and the nature of the primary solvent, diluent, and adjuvant within the droplets play an important role in primary and secondary distribution.

Over the years, the effectiveness of various control operations after two applications of fenitrothion varied from 60 to 80% for larval mortality and 30 to 65% for foliage protection (Nigam 1980). Results were measured indirectly by counting the number of drops of insecticide on Kromekote® cards; 15-20 drops/cm^2 gave effective results (Randall 1969). More recently, the droplets on one-year-old needles were counted and 0.5 - 1 drop >15 μm in size per previous year's needle gave effective results (Kettela, E.G. personal communication).

The spray droplets that reach the coniferous foliage are in the range of 10 to 60 μm (Himel 1969; Spillman 1976; Barry et al. 1977; Joyce and Spillman 1978; Barry and Ekblad 1978) but the droplet spectrum has recently been further refined to 15-55 μm under New Brunswick conditions (Picot et al. 1987) for optimizing effectiveness and minimizing drift. However a basic understanding of the dose transfer processes of insecticides to the pest after deposition on the host from air or ground application is lacking (Ekblad et al. 1979; Graham-Bryce 1983; Hall 1986).

The objectives of this study were to determine (1) the dose transfer mechanism of fenitrothion from primary contact surfaces in the microhabitat to the spruce budworm larvae after operational or simulated aerial application, and (2) the significance of the dose transfer mechanism for improving efficiency of foliage protection.

HIGHLIGHTS OF ACCOMPLISHMENTS

Dose transfer was investigated under field and laboratory conditions after aerial and simulated applications of insecticide. Various studies using fenitrothion formulations were initiated to evaluate the role of dose transferred to the larvae by contact through the cuticle, orally as a stomach poison, or as vapours through the respiratory system. Contact toxicity may occur by direct impingement of droplets on the larvae or by larvae crawling on residues adsorbed on foliage or on silk of the microhabitat. Stomach toxicity may occur through (a) larvae feeding on foliage that has adsorbed or absorbed residues of fenitrothion; (b) feeding on systemically translocated fenitrothion in the developing buds; and (c) oral contamination from droplets on silk.

Studies of direct contact, gross residual toxicity, vapour activity, systemic activity, and behaviour of budworm larvae in their microhabitats and droplet interactions have been carried out since 1982. Sixteen experimental sprays were applied to balsam fir, *Abies balsamea* (L.) Mill., by Grumman Avenger (TBM), or Cessna-188 aircraft using various fenitrothion formulations consisting of 210 g AI/ha [emulsion (EC) and flowable (FL) as 11% AI in water @ 1.45 L/ha and ultra ultra low volume (UULV) as 38% AI in Dowanol @ 0.46 L/ha].

Direct Contact Toxicity

Drop trays were used in the field to study the direct impingement of droplets on the larvae. Larval activity and fallout were observed 15-30 minutes after spraying. Direct impingement of droplets on larvae took place in only one morning spray out of 16 experiments, under special circumstances in the field, i.e., when 60% of the larvae were in the 5th instar (L_5) and the previous overnight temperatures and budworm activity were high, as evidenced by quantity of frass.

Residual Toxicity

Residual toxicity was studied using drop trays in the field. Results showed a gross effect of interactions among various modes of dose transfer, larval behaviour, host development, and weather. L_5 were most vulnerable to residues as compared with earlier instars because of their movement on treated surfaces. Initial high drop counts of L_5 on drop trays decreased with time as a result of deterioration of fenitrothion residue. Initially, L_2 were little affected by residues as the larvae were concealed in the needles, but with time and warm weather they emerged and wandered on the treated needle surfaces. L_2 drop tray counts increased with time. Few L_3 and L_4 were found on drop trays because the larvae were protected inside the developing buds; there was no change in the daily rate of fallout up to 4 days.

The bioassay and chemical analysis of foliage carried out for toxicity and deterioration of residues after aerial application of the insecticide revealed that an initial good deposit had a great impact on residual toxicity of fenitrothion. The results, so far, indicate that the order of residual toxicity of various formulations is UULV < EC < FL. Foliage protection by these formulations also appears to be in the same order.

Vapour Activity

Effect of fenitrothion vapour on the feeding behaviour of spruce budworm larvae was measured in the field by comparing damage to buds of branches protected from direct sprays with buds on neighbouring exposed branches of the same tree. This was accomplished by covering branches with paper bags during spraying and uncovering them after 30 minutes, when the spray cloud had settled. Thus in the treated plots, covered branches were exposed only to fenitrothion vapour. In check plots, similar sets of covered and uncovered branches were used in the evaluation of results. The fenitrothion vapour in the air after aerial application was measured using National Research Council (NRC) air samplers and chemical analysis was done at NRC, Ottawa. Field observations were made from 1982 to 1984. Air samples were not analyzed in the first year. An apparatus to observe the impact of fenitrothion vapour on larvae under laboratory conditions was developed in cooperation with Dr. L. Elias during 1983-1984.

Results demonstrated that vapour concentrations of fenitrothion observed under field conditions do not contribute to insect mortality or to foliage protection. Vaporization reduces the persistence of residues on foliage. If vaporization could be reduced by modifications to formulations then efficacy of fenitrothion would increase accordingly.

Systemic Activity

Systemic activity of fenitrothion was measured by covering buds with Plasticine® during spraying so that individual buds were shielded from deposition of spray droplets. It was hypothesized that insecticide from neighbouring exposed foliage and buds would translocate through the xylem and phloem transport systems. Biological, chemical, and physical measurements of fenitrothion droplets were made to determine systemic activity in the field experiments. Some translocation of fenitrothion was detected, by chemical analysis, in buds collected 72 h after application. However, these results were confounded by resinous material in the buds during early spring. No insecticidal effect from translocated fenitrothion was detected.

Budworm Larval Behaviour and Droplet Interactions

It was originally hypothesized that in operational spraying, toxicity of 0.5 - 1 drop of fenitrothion per previous year's needle was the result of chance encounters by larvae, while engaged in various activities governed by weather. This led to the study of droplet and budworm behaviour in the microhabitat during spray operations and to the observation of micro- and macro-weather. In New Brunswick, budworm populations in balsam fir are mostly in late L_3 and early L_4 instars during the first application of fenitrothion spray. Second applications of fenitrothion are carried out when most of the larvae are in L_4 and early L_5. Video recordings were made using an operating microscope, time-lapse video cassette recorder, and video and surveillance cameras to observe budworm behaviour and microhabitats at various stages of larval development. The same equipment was used to study the impaction of droplets on the microhabitat and the droplet-larval interface. Weather parameters were recorded on a micrologger. Information on canopy level weather was collected using sensors mounted on a meteorological tower located in the middle of the experimental plot, while other sensors were located on host tree branches to collect weather data near larval microhabitats. Temperatures for each quadrant were measured on the trees using thermocouples tied to twigs close to the budworm microhabitat and needle surface. Leaf wetness sensors were mounted on the needles. The micrologger was synchronized with the 12 surveillance cameras so that behaviour and weather were recorded simultaneously. The surveillance cameras were mounted on trees at heights of 5-6 m. Each camera recorded budworm behaviour for 3 min and the micrologger averaged weather parameters for this period.

Budworm microhabitat in balsam fir consists of various types of silk strands and new needles of growing buds (class 2 to 4, Dorais and Kettela 1982) at the time of first and second spraying. Fenitrothion formulation has to contact larvae within their microhabitats for maximum efficacy. The thickness of the silk strands varies from 2 to 12 μm and each size has a different function. The budworm remains within the confines of the silk inside the developing buds. Within the microhabitat, it spins an inner tube of very fine silk among the new needles. This tube is its living chamber and its foraging activity is confined to the new needles within the webbed area. The larva eats the needles from the middle of the developing buds. The larva is at all times in touch with the silk through its body hairs or legs. This silk is the lifeline for the larva and it is used for various functions. The larva usually crawls over the webbed silk which functions as a "road system" within its microhabitat. Changes in tension of the silk strands make the budworm aware of the outside environment and intruders. Silk strands are good collectors of dew and rain droplets. Behaviour studies showed that instrinsic factors like moulting, circadian rhythm, and energy requirement (hunger) of larvae govern their activity more than extrinsic factors like temperature, humidity, and wind speed. Larvae were relatively more active late in the evening (dusk) and very early morning (dawn) than in the daytime.

In the summer of 1985, it was observed that droplets of dyed fenitrothion flowable formulation were intercepted by silk strands after aerial application. Most droplets were < 15 μm and in some observations dead larvae were found within the microhabitat. Subsequent laboratory experiments carried out in the fall confirmed that webbing is a good collector of droplets. Droplets < 15 μm impinge more on the silk strands than on needles. When budworms in their microhabitats were sprayed with 8-12 μm droplets of 11% fenitrothion in isopropyl alcohol under laboratory conditions, 100% mortality of L_3-L_6 was observed.

In the summer of 1986, it was found that 210 g AI/ha of fenitrothion in UULV was more effective for foliage protection and larval mortality than the same amount of active ingredient per hectare of EC formulation. When the webbing from the treated microhabitats was chemically analyzed about 2 to 10 times more fenitrothion was found in UULV formulation samples than in EC samples.

During 1987 field trials with UULV formulation, an attempt was made to characterize the spectrum of droplets reaching the webbing. Because of evaporation and inadequate dye in the droplets, it was difficult to observe droplets < 10 μm. Droplets from 6 to 85 μm were observed in the webbing with number mean diameter (NMD) 37 μm and volume mean diameter (VMD) 42 μm. The VMD/NMD ratio is equal to 1.1 which is close to unity denoting a narrow range in size of droplets.

CONCLUSIONS

Direct contact of spray droplets on spruce budworm larvae is rare. Vapour and systemic activity of fenitrothion has little impact on larvae. Residual toxicity plays an important role in efficacy of fenitrothion. The mechanism of dose transfer appears to be through contaminated webbing and new needles within the microhabitat either by direct impingement of droplets or by secondary distribution of fenitrothion from old needles via rain and dew. Spray efficiency can be improved if droplets are targeted to the webbing and new needles, and if UULV application is practiced. Evening sprays, if practical, may be more effective than morning sprays because budworm actively feed and spin late in the evening and early morning, and also, fenitrothion deposits vaporise slower at night than during the daylight hours.

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DROPLET SPECTRA OF ATOMIZERS USED IN PEST CONTROL

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ABSTRACT — The droplet size spectra of some commercially available aerial sprayers were measured at selected operational conditions to determine the volume fraction of spray generated in the 15 to 55 μm (49×10^{-6} to 180×10^{-6} ft) size range. Three configurations of the Tee-jet, hydraulic type nozzles, were studied; the 11010, the 8002 and the 800050 nozzles. Two types of rotating cup atomizers were studied; the Micron X-1 and the Micron X-1 VP. Two types of rotating basket atomizers were also studied; the Micronair AU4000 fitted with a 20 mesh basket, 12.7 cm (0.42 ft) fan blades and the Beecomist 360 fitted with a 40 μm (131×10^{-6} ft), porous, stainless steel sleeve.

The fluids utilized in these experiments ranged in viscosity from 1 to 270 $\mathrm{mN \cdot s/m^2}$ (0.7×10^{-3} to 182×10^{-3} $\mathrm{lb_m ft \cdot s}$) and in surface tension from 30 to 76 mN/m (2.1×10^{-3} to 5.2×10^{-3} $\mathrm{lb_f/ft}$). Although simulants were used for much of the study, some work was done with the pesticide Dipel 132.

The testing was completed in a 1.02 m (3.35 ft) diameter aspirated flow wind tunnel. Sampling of the spray plume was by a multi-point grid traversing technique. The Particle Measuring Systems laser spectrometer system (FSSP-100 light scattering probe and the OAP-260X imaging probe) was employed as the droplet measuring apparatus. Problems of accuracy and limitations of this system are discussed.

In this survey of atomizing devices the volume fraction in the 15 to 55 μm (49×10^{-6} to 180×10^{-6} ft) size range is reported since this range is desirable for spruce budworm control. The Micronair AU 4000 operating at 233 Hz (14 krpm) and at flow rates less than 31.5 ml/s (0.50 USGPM) has 0.87 of the emission in this range. All of the other configurations studied show less desirable results.

RÉSUMÉ — Les spectres de gouttelettes obtenus avec certains pulvérisateurs aériens commerciaux ont été mesurés dans certaines conditions opérationnelles pour déterminer la fraction volumique pulvérisée se situant dans l'intervalle de 15 à 55 μm (49×10^{-6} à 180×10^{-6} pi). On a étudié trois configurations de buses de type hydraulique Tee-jet, soit les buses 11010, 8002 et 800050. On a également étudié deux types de pulvérisateurs à godet rotatif, soit le Micron X-1 et le Micron X-1 VP, ainsi que deux types de pulvérisateurs à panier rotatif, soit le Micronair AU4000 muni d'un panier de 20 mesh et de pales de 12,7 cm (0,42 pi), et le Beecomist 360 équipé d'un manchon en acier inoxydable poreux de 40 μm (131×10^{-6} pi).

Les liquides utilisés lors des expériences avaient une viscosité allant de 1 à 270 $\mathrm{mN \cdot s/m^2}$ ($0{,}7 \times 10^{-3}$ à 182×10^{-3} $\mathrm{lb_m pi \cdot s}$) et une tension superficielle allant de 30 à 76 mN/m ($2{,}1 \times 10^{-3}$ à $5{,}2 \times 10^{-3}$ $\mathrm{lb_f/pi}$). La plus grande partie des travaux a été effectuée avec des produits de simulation, mais le Dipel 132 a toutefois été utilisé dans certains cas.

Les essais ont été effectués dans une soufflerie aspirante de 1,02 m (3,35 pi) de diamètre. Pour l'échantillonnage du nuage pulvérisé, on a fait appel à une technique de polygonation de quadrillage en des points multiples. Le système de spectromètre laser *Particle Measuring Systems* (sonde à diffusion de lumière FSSP-100 et sonde à imagerie OAP-260X) a été utilisé pour mesurer les gouttelettes. On discute des problèmes de justesse et des limites de ce système.

Dans cette étude des dispositifs de pulvérisation, on indique la fraction volumique que représentent les gouttelettes dont la taille varie de 15 à 55 μm (49×10^{-6} à 180×10^{-6} pi), puisqu'il s'agit de l'intervalle recherché dans le cas de la lutte contre la tordeuse des bourgeons de l'épinette. Dans le cas d'un Micronair AU 4000 fonctionnant à 233 Hz (14000 tr/min) et à un débit inférieur à 31,5 mL/s (0,50 U.S.gal/min), 0,87 de l'émission est dans cet intervalle. Toutes les autres configurations donnaient de moins bons résultats.

INTRODUCTION

The optimum drop size range for defoliation control in spruce and fir forests by the eastern spruce budworm is 15 to 55 μm (49 × 10⁻⁶ to 180 × 10⁻⁶ ft) (Picot 1985). The current aerial application of chemical pesticide/water emulsions with Teejet 11010 nozzles relies upon evaporation of the water component to reduce droplet size. Typically the emitted formulation is 85 volume percent water. After total evaporation of the water, droplet diameters reduce to 53 percent of the original emitted diameter. An effort has been made to discover an atomizer that will produce a maximum emitted volume of drops in the optimum size range. Atomizer flow capacity also plays an important role in improving operations.

Full scale atomizer characterizations are carried out in a 1.02 m (3.35 ft) diameter aspirated flow wind tunnel. A technique has been developed to produce drop size number and volume frequency spectra. The droplet measuring and data acquisition system consists of a Forward Scattering Spectrometer Probe, FSSP-100, an Optical Array Particle Size Spectrometer, OAP-260X and a Particle Data System, PDS-300. These instruments are manufactured by Particle Measuring Systems, Boulder Colorado, U.S.A. The resulting drop size distributions are on a temporal basis. A comparative study of some commercially available atomizers is presented.

EXPERIMENTAL METHODS

Wind Tunnel

An aspirated flow wind tunnel, Fig. 1, is dedicated to atomizer characterization. The test section is 1.02 m (3.35 ft) in diameter and 3.05 m (10 ft) long. The overall length of the tunnel is 7.73 m (25.4 ft). Tunnel air speed up to 75 m/s (246 ft/s) can be generated by the 153 kilowatt (205 hp) diesel engine which belt drives a 1.37 m (4.49 ft) axial flow fan. This whole apparatus is mounted on a trailer. Actual pesticide formulations may be tested at a remote location.

The atomizer being characterized is mounted in the test section 1 meter (3.28 ft) from the sensing probe. The atomizer is supported by an air foil shaped boom which can be set at various points across the diameter of the tunnel. Metered fluid is supplied via a conduit inside the boom. The sensing probes can be traversed at a controlled rate by a screw drive assembly coupled to a 560 watt (0.75 hp) electric motor.

Forward Scattering Spectrometer Probe

Figure 2 shows the optics of the Forward Scattering Spectrometer Probe, FSSP-100. Particles passing through the beam within the sample area are measured by an electronic comparison of the relative quantity of forward scattered light to predetermined voltage levels in a pulse height analyzer module. The sample area is defined by combined electronic and optical considerations. This probe, when operating on range A, measures particles in the size range from 2.0 to 47.0 μm (6.3 × 10⁻⁶ to 154 × 10⁻⁶ ft), for water. Counts are classified into 15, 3 μm (9.8 × 10⁻⁶ ft) wide size class intervals, or channels.

Output particle sizes from this probe must be corrected for the refractive index of the fluid and for instrument calibration (Cerni, 1983, Picot loc. cit.). The refractive index correction is based on theoretical Mie light scattering calculations (Bontemps, 1983). Instrument calibration is based on volume median diameter values for glass bead samples, measured with a calibrated eyepiece. These are compared to peak number FSSP-100 output diameters which are corrected for the refractive index of glass. Instrument calibration is performed before and after each test. For atomizer performance comparison studies, the following equation relates FSSP-100 output to a corrected diameter by a factor. This factor represents both instrument size calibration and a correction for the refractive index of the formulation, and is a function of droplet size and refractive index (van Vliet and Picot, 1988).

$$D_{ci} = a \cdot D_{mi} \qquad (1)$$

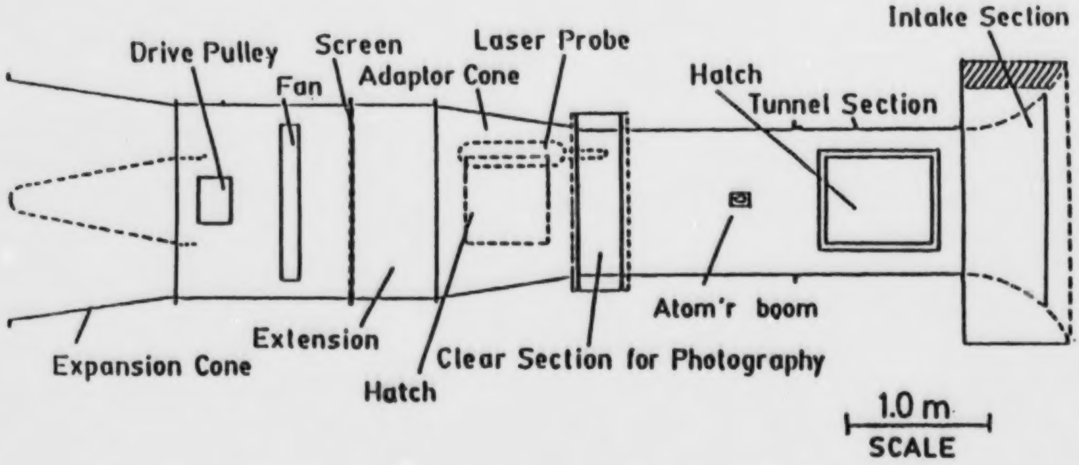

FIGURE 1: SKETCH OF WIND TUNNEL

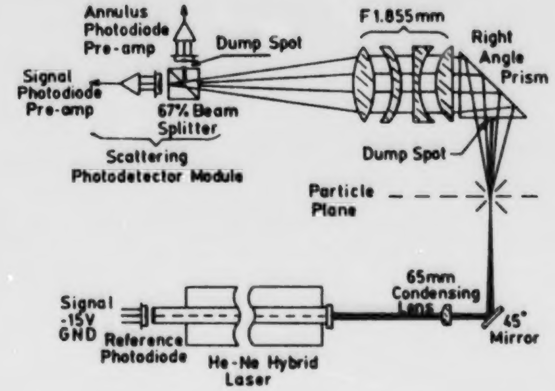

FIGURE 2: FSSP-100 OPTICS

The FSSP-100 is capable of measuring the amount of time which it has been active counting and sizing drops during a sample period. This is output as percent activity. Percent Activity is used to correct particle counts for electronic dead time losses as follows:

$$N_{ci} = N_i/(1 - A \cdot k) \tag{2}$$

where

N_{ci}	is the corrected count
N_i	is the FSSP-100 output count
A	is activity in percent
k	is a constant, 0.007, supplied by the manufacturer

Total volume flux of emitted spray from an atomizer is calculated by equation 3.

$$\text{Total volume flux} = \frac{\pi}{6} \Sigma N_{ci} \cdot D_{ci}^3 \cdot L \cdot W/Sa \cdot t \tag{3}$$

where

L	is the length of probe traverse
W	is the width of atomizer point wise traverse increment
Sa	is the sample area
t	is the traverse time

By computing total volume flux in this manner we have defined an absolute time basis for the spectrum measurement.

Optical Array Particle Size Spectrometer

The Optical Array Particle Size Spectrometer, OAP-260X, probe measures the projected image of a particle in the sample area by electronically counting the number of photo diodes that are shadowed. The optics of this instrument are shown on Fig. 3. Drop size is related to the number of elements shadowed, the width of the elements, and the magnification of the optics. Sample area is a function of drop diameter. Particle number data is classified into 62 size classes for nominal sizes from 7.10 to 625 μm (23.3×10^{-6} to 2050×10^{-6} ft).

Instrument calibration (van Vliet and Picot, 1988), is based on the volume median diameter values from glass bead samples measured with a calibrated microscopic eyepiece compared to that calculated from probe output. Probe output diameters are then corrected by equation 4.

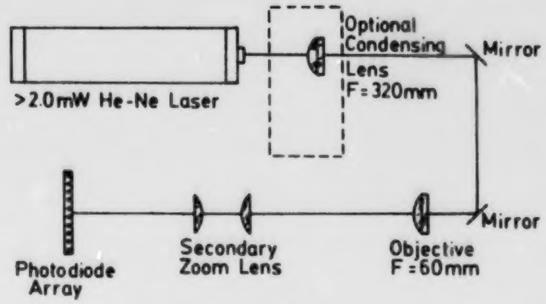

FIGURE 3: OAP-260X OPTICS

$$D_{ci} = D_{mi} \cdot b + c \tag{4}$$

D_{ci}	is the corrected diameter
D_{mi}	is the nominal output diameter
b and	c are calibration constants

A check of this equation by measuring monodisperse drops of 2-propyl alcohol for two drop sizes, shows consistent results with the above equation.

The OAP-260X probe reports erroneous total volume flux as calculated by equation 3. For atomizer tests with low fluid flowrates high fluxes are reported. The opposite is true for high flowrate tests. There are several competing factors contributing to this problem: there is an inherent spectral broadening by the OAP-260X, (Hovenac et al., 1985 and van Vliet & Picot, 1988) a large sample area for this probe results in higher probability of coincidence, and the large sample area also contributes to increased electronic dead time.

Several modifications have been made in an attempt to reduce these problems. Special probe tips were constructed to reduce the maximum depth of field from 6.1 cm (0.20 ft) to 1.1 cm (0.036 ft). Changes to software were made for the reduced sample areas. A bulk area reject circuit was installed to cope with coincidence events. These modifications have had a limited effect. The problem of spectral broadening is reduced somewhat by the bulk area reject circuit. Inherent spectral broadening by the photo diode array still remains. No function is yet available to deal with the dead time loss of counts. A method to produce a complete drop size spectra is presented below.

Treatment of Data

In order to report a complete drop size spectrum both probes are traversed independently through a spray plume at a controlled, continuous rate. Probe traverses are done at each 5.0 cm (0.164 ft) point wise, horizontal traverse of the atomizer. This is so that the whole spray plume is sampled. Probe outputs have their appropriate corrections made for size and dead time, FSSP-100, and size only, OAP-260X.

The total volume flux given by equation 3 is calculated for both probes. The FSSP-100 data as treated above is considered absolute. The information above 45.5 μm (149×10^{-6} ft), FSSP-100 nominal diameter, from the OAP-260X is spliced onto the FSSP-100 data and multiplied by a factor so that an overall mass balance restriction is met. If the combined FSSP-100, OAP-260X reported spectrum is grossly discontinuous at the splicing point the test will be repeated.

Problems arise when non representative sampling occurs i.e. structured spray plumes, fast sampling rates, dense spray pattern, or a single traverse of the probes through the spray plume. These problems are overcome by complete detailed traverses of the probes over the total spray plume. In cases when the plume is structured or dense, point wise probe and atomizer sampling on a grid is required. In general, spectrum measurements performed in this manner are adequate.

Experimental Results

A series of tests, Table 1, have been carried out on commercially available atomization equipment, Fig. 4. The tests were performed for the most part with simulant formulations, with the exception of test 8. Fluid properties were measured at operational temperatures as reported in Table 2. Figure 5 shows the relationship between viscosity and shear rate for Dipel 132 as measured

TABLE 1: Atomizer Performance

Test #	Atomizer description	Formulation	Flowrate mℓ/sec	Airspeed (m/s)	Cumulative Volume Fraction in 15-55 μm drops	# Of 15-55μm drops per ml of formulation	# Of 15-55 μm drops per second per atomizer
1	Teejet 11010 oriented 90° to air flow	1	63.5	64	0.167	1.14×10^7	7.24×10^8
2	Teejet 8002 oriented 90° to air flow	1	13.2	63	0.187	1.26×10^7	1.66×10^8
3	Teejet 800050 oriented 90° to air flow	1	3.2	62	0.284	3.29×10^7	1.05×10^8
4	Micron X-1 set for maximum rotational velocity	1	1.5	45	0.463	4.09×10^7	0.61×10^8
5	Micron X-1 variable pitch set for maximum rotational velocity	1	1.5	45	0.442	4.29×10^7	0.64×10^8
6	Beecomist 360 40 μm stainless steel sleeve rotating at 232 Hz	2	12.7	42	0.543	3.62×10^7	4.60×10^8
7	Micronair AU4000 20 mesh basket rotating at 233 Hz	3	30.7	49	0.834	5.57×10^7	17.10×10^8
8	Micronair AU4000 20 mesh basket rotating at 233 Hz	4	31.5	49	0.729	4.50×10^7	14.18×10^8

FIGURE 4: ATOMIZERS, FROM LEFT TO RIGHT TEEJET, MICRON X-1, MICRON X-1 VP, MICRONAIR AU4000 AND BEECOMIST 360.

TABLE 2: Formulations

Fluid	Composition (% vol)	Surface tension (mN/m)	Viscosity (mN·s/m²)	T (C°)
1	91% water 9% 2 propanol	48	4	12.5
2	deiceing fluid	45.0	35.9	-8.5
3	80% water 20% 2-propanol + 10 wt % salt	38.0	5.1	-5
4	100% Dipel 132	29.1	See Fig. 5	23

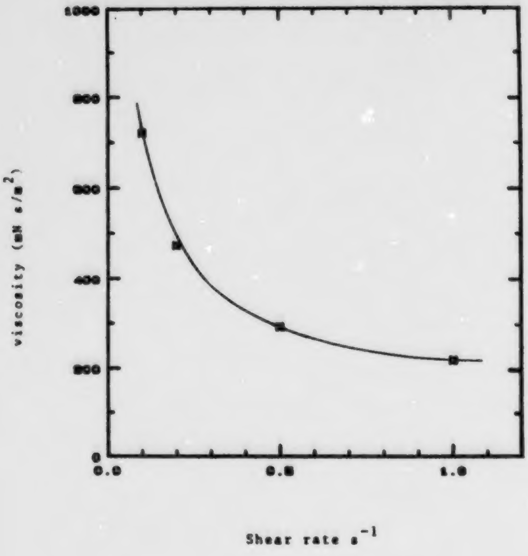

FIGURE 5: VISCOSITY (mN·s/m^2) VS. SHEAR RATE (s^{-1}) FOR DIPEL 132.

with a Brookfield viscometer. At shear rates above 1 s^{-1} the viscosity of the Dipel 132 formulation tends to become constant. When this fluid is atomized by a Micronair AU4000 rotating at 233 Hz, much larger shear rates than this are expected to occur.

For comparison purposes it is best to perform atomizer characterizations with simulant formulations that are inexpensive and nontoxic. This is the case for tests 1 through 5 and test number 7. Trends are observed for testing with the simulant formulations. Optimum atomizer performance is selected and testing is completed with a simulant formulation that closely matches the physical properties of the desired pesticide formulation, test 6. Actual pesticide formulations can be tested. This is the case for test number 8.

Typical number and cumulative volume fraction distribution curves are shown, Fig. 6, 7 and 8 for test numbers 3, 4 and 6 respectively. The number distribution curve in each case represents a mass balance of the spray emitted from the atomizer at the specified operating conditions. The units of N are number of drops per μm per second. From these plots the cumulative volume fraction in the 15 to 55 μm (49 × 10^{-6} to 180 × 10^{-6} ft) size range can be determined. Since flowrate considerations represent practical limitations for choosing the best atomizer, the emission rate of 15 to 55 μm (49 × 10^{-6} to 180 × 10^{-6} ft) drops has been calculated on a per unit volume and on a per unit time basis from the number distribution data, Table 1.

Three teejet flat fan nozzles were tested at approximately 63 m/s (207 ft/s) air speed, tests 1, 2 and 3 Table 1. In each case nozzle orientation was 90 degrees to the air flow. The fluid pressure at the nozzle was 276 kN/m^2 (40 psig) for each test. As nozzle orifice size decreased the trend was toward more spray volume in the optimum size range. More optimum sized drops were produced per ml of formulation which would tend to improve economy but since flow rate decreases as nozzle size decreases, for a constant pressure, the emission rate per unit time also declines.

Two models of a rotating cup atomizer were studied. The two units are essentially the same except for the fan drive system. The X-1 unit has interchangeable fans of varying pitch while the V.P. unit requires rotation of each individual fan blade to set rotational velocity. Formulation is supplied to a 5.0 cm (0.164 ft) diameter rotating, surrated edge, cup via a hollow central shaft. The cup rotates on this shaft. For our tests, the blade pitch was set to produce maximum rotation in a 45 m/s (148 ft/s) air flow. Rotational velocity depends upon fluid flow rate which was 1.5 ml/s (0.024 USGPM) in these tests. Fluid viscosity also affects rotational velocity. In these tests this was not studied.

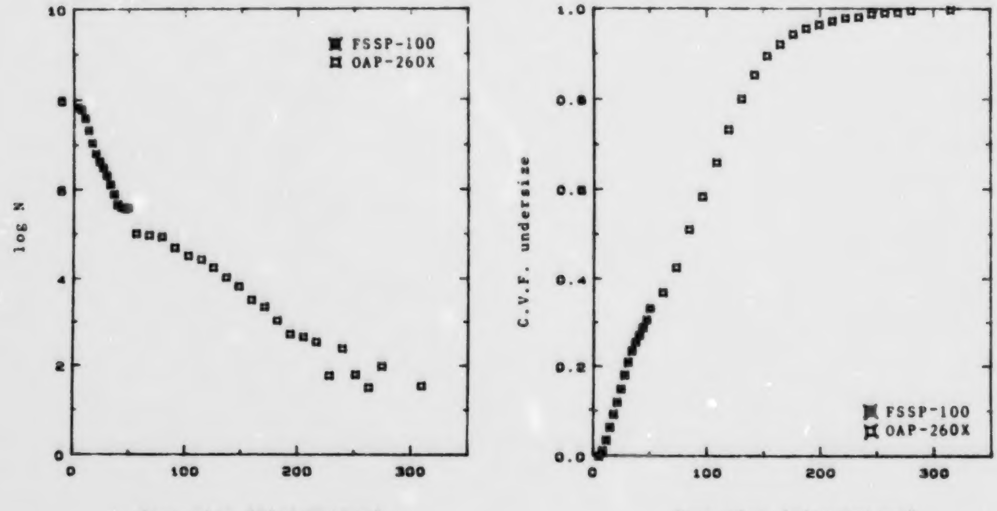

FIGURE 6: NUMBER DISTRIBUTION CURVE (LEFT), CUMULATIVE VOLUME FRACTION CURVE (RIGHT) FOR THE TEEJET 800050 NOZZLE ORIENTED 90° TO A 62 m/s AIR FLOW, FORMULATION 1 SUPPLIED AT 3.2 ml/s.

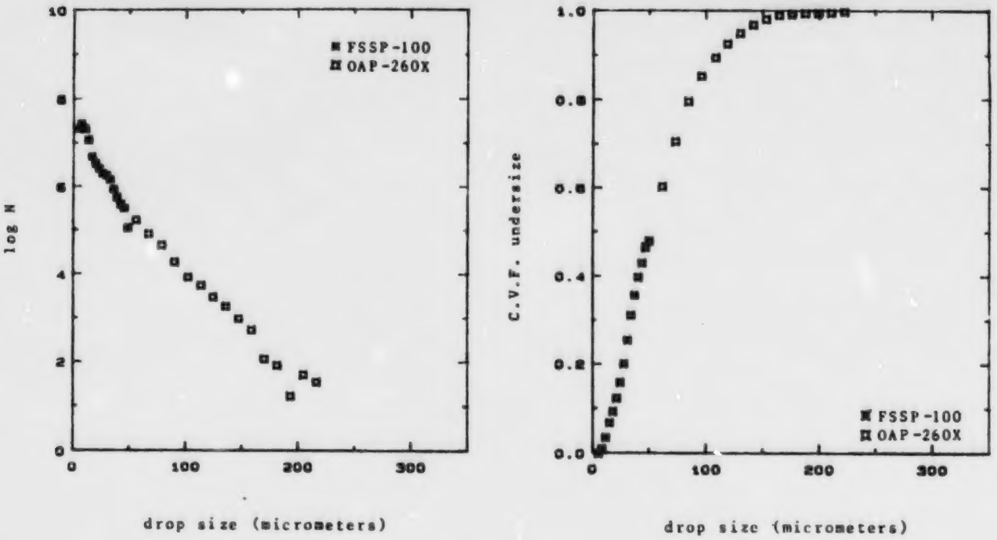

FIGURE 7: NUMBER DISTRIBUTION CURVE (LEFT), CUMULATIVE VOLUME FRACTION CURVE (RIGHT) FOR THE MICRON X-1, SET TO MAXIMUM ROTATIONAL VELOCITY IN A 45 m/s AIR FLOW, FORMULATION 1 SUPPLIED AT 1.5 ml/s.

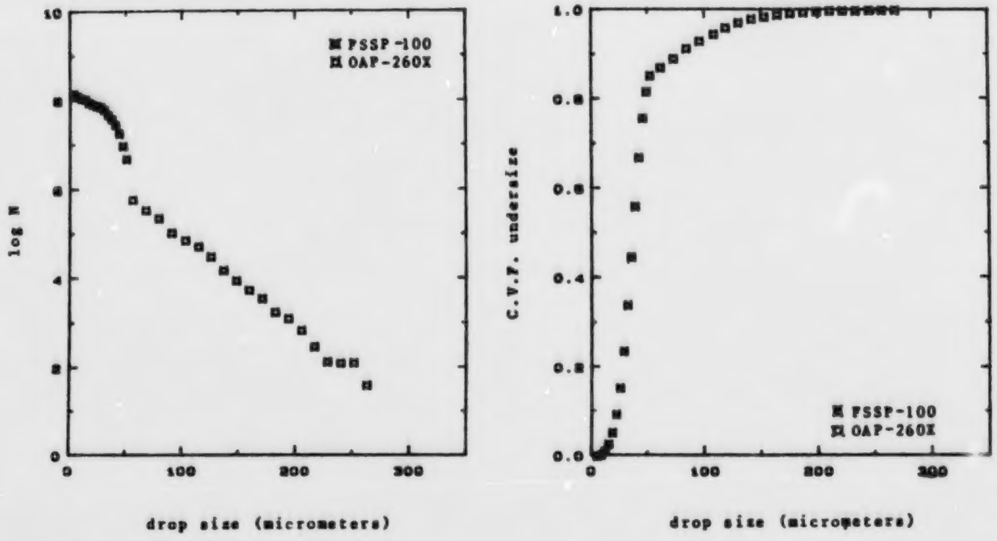

FIGURE 8: NUMBER DISTRIBUTION CURVE (LEFT), CUMULATIVE VOLUME FRACTION CURVE (RIGHT) FOR THE MICRONAIR AU4000 FITTED WITH A 20 MESH BASKET, 12.7 cm FAN BLADES, ROTATING AT 233 Hz IN A 49 m/s AIR FLOW, FORMULATION 1 SUPPLIED AT 30.7 ml/s.

Both Micron units performed equally well showing 0.463 and 0.442 CVF in the optimum size range for the X-1 and the V.P. units respectively. Such low flow rates are required to achieve this degree of atomization that these units are not practical for spruce budworm spray application.

The Beecomist 360 unit is an electrically driven, direct current, rotating sleeve atomizer. This unit comes equipped with a variety of sleeves. Previous study (Picot loc. cit.) shows that 100 percent of the emitted spray is sub 55 μm (180 × 10^{-6} ft) particles. The following test conditions prevailed; 40 μm (131 × 10^{-6} ft) porous polyester sleeve rotating at 120 Hz (7.2 krpm), water at 20.2 ml/s (0.32 USGPM) and the air speed was 40 m/s (130 ft/s). The performance of this atomizer deteriorates when formulation viscosity is increased, Test 5 Table 1. Note that only 54.3 percent of the volume is the optimum range for formulation 2. Formulation 2 is a simulant for the fenitrothion/water emulsion currently used for spruce budworm spray application in New Brunswick.

The Micronair AU4000 has been extensively characterized (van Vliet and Picot 1987). This unit shows excellent performance at flowrates less than 33.3 ml/s (0.53 USGPM) at a rotional velocity of 233 Hz (14 krpm), for any formulation ranging in viscosity from 1 to 270 mN·s/m^2 (0.7 × 10^{-3} to 182 × 10^{-3} lb$_m$/ft sec) and in surface tension from 30 to 76 mN/m (2.1 × 10^{-3} to 5.2 × 10^{-3} lb$_f$/ft). Test 7 shows that 83.4 percent of the volume emitted is in the optimum size range. Comparison of test 7 to test 1 shows that the AU4000 unit delivers 2.3 times more optimum drops per second at half of the flow rate requirement.

Test number 9 was performed with the Dipel 132 formulation. The AU4000 shows good performance at increased viscosity for this concentrated bacterial pesticide formulation. Dipel 132 is a two phase formulation containing solid particles in suspension. The problem of two phase light scattering by the FSSP-100 has not been addressed here. This makes this characterization somewhat less accurate until the two phase light scattering problem is solved.

CONCLUSIONS

Droplet spectrum characterizations can be completed relatively quickly and quite accurately by the method presented. Aerial spray efficacy can be improved through atomizer comparison studies when the optimum drop size range is known.

The Micronair AU4000 atomizer is currently the best suited atomizer for spruce budworm spray application. This unit is versatile and may be used in other applications with some adjustments.

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FENITROTHION DEPOSITS ON SIMULATED AND LIVE SURFACES DURING AN AERIAL SPRAY TRIAL IN NORTHERN ONTARIO

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ABSTRACT — Initial deposit of fenitrothion sprayed aerially over a boreal forest were studied near Searchmont, Ontario. Two plots, approximately 23 ha (plot P1) and 49 ha (plot P2), were sprayed with an emulsion formulation of fenitrothion at a dosage rate of 280 g active ingredient (AI) in 1.5 L/ha using a fixed-wing aircraft fitted with Micronair® AU3000 atomizers. Artificial samplers made of aluminum coils to simulate balsam fir foliage, and aluminum foil to simulate white birch leaves and three species of wild flowers (chokecherry, blueberry and strawberry flowers) were placed in the plots prior to spray application along with conventional Kromekote® card/glass plate units. All samplers and live foliage were collected one hour after application; fenitrothion was extracted and analysed by gas-liquid chromatography.

Droplet analysis on Kromekote cards showed that the mean droplets/cm^2, and the number and volume median diameters, were nearly uniform at all sampling sites. Quantification of spray deposits on the simulated fir foliage indicated definite gradients in deposit concentrations, decreasing from top to bottom crown, and from periphery to inner tree crown. In the birch tree crown such gradients were not observed. Generally the artificial leaves acted as better collectors of spray droplets than the natural leaves.

Deposits of fenitrothion on different artificial and natural wild flowers varied depending on their geometrical shapes and surface characteristics. The planar strawberry and tubular chokecherry blossoms received more deposits than the bell-shaped blueberry flowers.

The mean deposit values, expressed in ng/cm^2, showed a wide variation, although there was generally a good relationship between the deposits on the simulated and natural surfaces.

RÉSUMÉ — Des dépôts initiaux de fénitrothion pulvérisé du haut des airs sur une forêt boréale ont été étudiés près de Searchmont (Ontario). Deux placettes d'environ 23 ha (P1) et 49 ha (P2) ont été arrosées avec une émulsion de fénitrothion à raison de 280 g d'ingrédient actif/1,5 L par hectare; des aéronefs à voilure fixe munis d'atomiseurs Micronair® AU3000 ont été utilisés. Avant l'arrosage, on a mis dans les placettes, en plus des cartes Kromekote® et des plaques de verre ordinairement employées, des collecteurs artificiels, soit des rouleaux d'aluminium pour simuler le feuillage du sapin baumier et des feuilles l'aluminium pour le feuillage du bouleau à papier et trois espèces de fleurs sauvages, celles du cerisier, de la myrtille d'Amérique et du framboisier. Tous les collecteurs et le feuillage vivant ont été recueillis une heure après l'arrosage, et le fénitrothion, une fois extrait, a été analysé par chromatographie en phase liquide-gaseuse.

L'Analyse des gouttelettes sur les cartes Kromekote a démontré que le nombre moyen de gouttelettes par centimètre carré, et le diamètre médian en fonction du nombre ($D_N \cdot 5$) et le diamètre médian en fonction du volume ($D_V \cdot 5$) étaient presque uniformes pour tous les endroits échantillonnés. La mesure des dépôts sur le feuillage artificiel de sapin a révélé qu'il existait des gradients de concentration: celle-ci diminuait de la cime vers la base, et de la périphérie vers le milieu. Dans le cas du bouleau, de tels gradients n'ont pas été observés. En général, les feuilles artificielles étaient de meilleurs collecteurs de gouttelettes que les feuilles naturelles.

Les dépôts de fénitrothion sur différentes fleurs sauvages artificielles et naturelles variaient en fonction de leur forme géométrique et de leur surface. Les fleurs plates du framboisier et tubulaires du cerisier ont reçu plus de dépôts que les fleurs en forme de cloche de la myrtille.

La valeur moyenne des dépôts, exprimée en nanogrammes par centimètre carré, variait considérablement, mais en général on a constaté un bon rapport entre les dépôts sur les surfaces simulées et naturelles.

INTRODUCTION

In forestry applications of pesticides, the potential adverse side effects on non-target organisms inhabiting the target site are proportional, to some extent, to the initial deposits obtained in various components of the forest ecosystem. Therefore, it is important to know how much of the initial residues are present in different parts of the sprayed areas. The use of simulated samplers for deposit collection provides many advantages. The chemical will not metabolize as fast on the simulated samplers as in the biological ones, so that a more accurate picture of the active ingredient (AI) deposits can be obtained. Secondly, the extraction and column cleanup procedures for gas-liquid chromatography (GLC) are much simpler because of the absence of interfering materials present in the biological samples. Therefore, a study of the relationship between the deposits on simulated and live surfaces would provide information on the suitability of using such surfaces for deposit collection.

In the present study, aerial spray deposits were collected on (i) aluminum coils shaped to simulate balsam fir foliage; (ii) aluminum foil shaped to simulate white birch leaves and three types of wild flowers (i.e., chokecherry, blueberry and strawberry flowers); (iii) natural balsam fir foliage and the three types of flowers. The objectives were (a) to investigate the interrelationships between the deposits on natural and simulated surfaces and (b) to examine the relative deposits on different parts of the forest ecosystem during pesticide applications.

MATERIALS AND METHODS

Experimental Plots

Two plots, P1 and P2, were established in a boreal forest area approximately 10 km north of Searchmont (coordinates, N 46°52′, W 84°00′) in Township 24 R11, Algoma District, Ontario. Plot P1 (23 ha) was dominated by trembling aspen, pin cherry and small (< 2 m high) white spruce. Numerous wildflowers, shrubs and grasses made up the understory. Plot P2 (49 ha) was a somewhat wetter site with considerable amounts of cedar and alder, as well as white birch and balsam fir trees. The mean canopy height in both plots was around 8 m.

Sampling Trees and Shrubs

Six trees, each of balsam fir, *Abies balsamea* (L.) Mill., and white birch, *Betula papyrifera* Marsh. [total height 7 ± 1 m; crown height 6 ± 0.5 m; crown diameter (base) 2.5 ± 0.5 m; and diameter at breast height 11 ± 3 cm; for both species] were selected randomly in plot P2, along a line transecting it across the centre. For sampling flowers, chokecherry (*Prunus virginiana* L.), blueberry (*Vaccinium angustifolium* Ait.) and strawberry (*Fragaria virginiana* Duchesne) were selected randomly in P1 (wherever available) along a sampling line cutting across the middle of the plot perpendicular to the aircraft flight lines.

Ground Sampling Units

To determine the ground deposit levels and the droplet size spectra, the conventional Kromekote® card/glass plate units (Randall, 1980) were used. In plot P2, 12 such units (six near the clearings of the balsam fir and the other six near the clearings of the birch trees) were placed, each on an aluminum stand 15 cm above forest floor, at 1 h prior to spray application. Four similar units were placed in each of four clearings spaced across plot P1 to provide a total of 16 units.

Simulated Samplers

For simulating fir foliage, aluminum coil clusters (individual coils having a diameter similar to that of mature balsam fir needles) were used (Sundaram et al., 1986). These were placed on fir tree crown using a pole pruner at 1, 3 and 5 m heights, starting from the crown tip. These heights represented the top, middle and bottom sampling sites (Table 1) of the tree crown. At each of the mid and bottom crown levels, one cluster was placed horizontally near the stem of each tree representing respectively, the mid-interior and bottom-interior sampling sites of the tree.

Aluminum branches containing 10 to 15 aluminum leaves, having the same dimensions as the natural birch leaves, were placed on the birch trees, at the same heights and locations as those on the fir trees.

In plot P1, artificial aluminum coil samplers, corresponding to the shapes of chokecherry, blueberry and strawberry blossoms, and these were suspended either singly, or in clusters, 1.5 m off the ground (chokecherry) or elevated on "stalks" about 30 cm off the ground (blueberry and strawberry).

Spray Formulation

Technical fenitrothion (Sumithion®, Sumitomo Chemical Co., Osaka, Japan) 15% (v/v), mixed with Atlox® 3409F (Atkemix, Brantford, Ontario) 1.5%, Dowanol® TPM (Dow Chemical, Sarnia, Ontario) 1.5%, Rhodamine B (Allied Chemical, Morristown, New Jersey, USA) 2%, and water 80%, served as the spray formulation.

Spray Application and Meteorological Conditions

A Cessna 188 aircraft equipped with four Micronair® AU3000 atomizer units with blade angles set at 35° applied the spray at a dosage rate of 280 g AI in 1.5 L/ha and an emission rate of 18 L/min, flying at a speed of 160 km/h with a swath interval of 45 m. Spray was applied at a height of 15 m above the tree canopy and at right angles to the prevailing wind, on June 14, 1985, between 0715 and 0800 h. The approximate meteorological conditions that existed at the time of spraying were: wind speed 2 ± 0.5 km/h, temperature 15 ± 1°C, relative humidity 80% and the cloud cover 0/10.

Sampling and Storing Procedures

All samples, both natural and simulated, were collected 1 h after spray application.

1. Sampling of Live Fir and Birch Foliage

For the study of the vertical distribution of fenitrothion in the peripheral foliage, one branch, 30 cm long, was clipped from the location adjacent to the simulated sampler, from each of the top, mid and bottom crown levels. For the radial distribution study, branch segments were taken from the mid-interior and bottom-interior levels, adjacent to the positions of the simulated samplers. All samples were placed immediately in portable coolers and stored at 0°C.

2. Sampling of Live Flowers

Samples of chokecherry, blueberry and strawberry flowers were individually picked by using tweezers, placed in Mason jars and were stored at once in the coolers at 0°C.

3. Sampling of Simulated Surfaces

The simulated aluminum branches of the fir and birch trees, the aluminum flowers of the three types of shrubs, and the glass plates of the Kromekote card/glass plate units, were all collected, and immediately transported to the nearby field laboratory (improvised), where the deposits of AI were extracted at once from the samplers using ethyl acetate as the solvent. The extracts were placed in amber-colored bottles and stored in coolers at 0°C.

The Kromekote cards were collected, wrapped in aluminum foil and stored in the dark in a desiccator.

4. Storage Procedures

The samples which were placed in portable coolers at 0°C, were quickly transported to the Sault Ste. Marie laboratory, where they were stored in a freezer at -20°C until GLC analysis.

Column Cleanup and GLC Analysis

All samples were analysed for fenitrothion deposits by the GLC method of Sundaram and Sundaram (1987). Extracts of the live samples required column cleanup before GLC analysis. However, those of the simulated samplers were analysed directly by GLC without any column cleanup procedures.

The minimum detection limit (MDL) of quantification was fixed at 0.01 μg/g (10 ng/g) of the extract for all the samples, although a much lower MDL can be obtained for these substrates. The AI deposits in ng/g were converted into ng/cm² (Tables 1 and 2), using the surface areas of the natural and simulated samplers, and the mass per natural leaf and flower, so that a comparative treatment can be made between the deposits on the simulated and natural surfaces. The deposits on the glass plates, however, were converted into g AI/ha Table 3), using the surface area of the plates.

TABLE 1: Fenitrothion deposits (mean ± SD, ng/cm²) on simulated and live fir and birch foliage

	Location in tree crown					
Samplers	**Top**	**Middle**	**Bottom**	**Mid-interior**	**Bottom-interior**	**Mean**
Simulated fir needles	431± 204	301± 208	110± 68	68± 11	65± 24	195± 138
Live fir needles[a]	75± 20	54± 30	43± 8	41± 13	30± 3	49± 17
Simulated birch leaves	207± 53	226± 106	262± 116	198± 57	155± 59	210± 91
Live birch[b] leaves	66± 24	90± 24	71± 29	72± 16	64± 18	73± 10

[a]: Average surface area, width, length and mass per fir needle are respectively 0.40 ± 0.07 cm², 0.07 ± 0.01 cm, 1.40 ± 0.06 cm, and 0.006 ± 0.002 g.

[b]: Average surface area (both sides) and mass per birch foliage are respectively 62 ± 5 cm² and 0.21 ± 0.03 g.

TABLE 2: Fenitrothion deposits (mean ± SD, ng/cm²) on simulated and natural flowers

	Samples		
Samplers	**Chokecherry (tubular)**	**Blueberry (bell shape)**	**Strawberry (planar)**
Simulated	228 ± 167	163 ± 84	362 ± 173
Natural	130 ± 17	31 ± 3	85 ± 9
Mass per flower (g)	0.012 ± 0.002	0.014 ± 0.003	0.021 ± 0.005
Surface area per flower (both sides) (cm²)	0.800 ± 0.230	0.830 ± 0.140	1.550 ± 0.150

TABLE 3: Droplet size spectra and deposit levels on Kromekote® card/glass plate units

Plot No. and card location	Droplets per cm²	D_{min}[a] (μm)	D_{max} (μm)	$D_{N.5}$ (μm)	$D_{V.5}$ (μm)	Amount deposited[b] (g AI/ha)	Percent deposited[b]
P2; near fir trees	16 ± 8	10	114	35 ± 4	56 ± 11	82 ± 33	29 ± 12
P2; near birch trees	12 ± 9	10	120	37 ± 5	60 ± 20	64 ± 36	23 ± 13
P1; near flower shrubs	16 ± 10	10	120	36 ± 6	59 + 15	65 + 28	23 ± 10

[a]: The minimum detection limit of the droplet sizing technique was 10 μm.

[b]: Determined by gas-liquid chromatographic analysis of glass plate deposits.

Droplet Analysis on Kromekote Cards

Droplet stains on the Kromekote cards were analysed by the National Aeronautical Establishment of the National Research Council of Canada, Ottawa, using the Flying Spot Scanner (Drummond, 1980). The data obtained from the six cards (placed near the fir or birch trees) were pooled and grouped according to diameter classes to evaluate (Sundaram et al., 1985) the number and volume median diameters ($D_{N \cdot 5}$ and $D_{V \cdot 5}$ respectively), maximum diameter (D_{max}), and droplet density (droplets/cm^2) (Table 3). The means and standard deviations were calculated using data obtained for individual cards. Similar data on droplet size characteristics were also obtained for the sixteen cards placed in plot P1, near the flower shrubs.

The minimum detection limit of the droplet sizing technique (Sundaram et al., 1985) was 10 μm.

RESULTS AND DISCUSSION

Size Spectra, Droplet Density and Deposits in g AI/ha

The data on droplet size spectra, droplet density and AI deposits on glass plates were subjected to analysis of variance tests for statistical treatment. No significant difference was noted in any of the droplet or deposit parameters, among the three locations (i.e., those near the fir trees, birch trees and flower shrubs) selected in the two plots. This is clearly evident from the similar mean values and high standard deviations obtained (Table 3) for all parameters. This finding indicates that the upper end of the droplet size spectrum was uniformly distributed throughout the sampling areas.

Relationship Between Deposits on Simulated and Live Surfaces

In both plots, the simulated surfaces received higher AI deposits than the natural ones. This trend was observed on all the three types of surfaces, viz., fir needles, birch leaves and flowers (Tables 1 and 2). It appears that biological samples, irrespective of their surface characteristics tend to receive lower deposits than metallic objects. The reason could be that biological surfaces are weaker conductors of electrical charges than metal surfaces. As a result, the metal surfaces might have received a greater number of droplets than the biological surfaces. Or, the chemical might have partly degraded in the biological samplers within the first hour of post-spray sampling, a phenomenon which could not have occurred on the metallic samplers. These aspects, however, require further investigations.

Vertical Distribution of Deposits in the Periphery of the Tree Crown

From the mean deposit levels listed in Table 1, it is evident that the top portion of the fir tree crown received the maximum deposits, and that the levels decreased progressively from the top to the bottom crown. This trend was observed in both simulated and natural fir foliage. This observation is in agreement with that reported by others (Carman and Jeppson, 1974; Yates et al., 1974; Spillman and Joyce, 1978; Armstrong and Yule, 1978; Barry et al., 1982; Barry, 1984; Sundaram et al., 1986). This is due to the filtration of spray droplets by the conifer foliage. However, such vertical gradients in deposits were not apparent in the birch tree crown, since no marked differences were noticeable from top to bottom. These differences between the two tree species could be due to the distribution of foliage within the tree crown and due to the different shapes of leaves of the two tree species. As a result, different micrometeorological factors could be associated with the two tree crowns, causing differences in droplet deposition patterns and canopy filtration of droplets.

Radial Distribution of Deposits in the Tree Crown

Similar to the vertical distribution of the chemical in the tree crown, the radial distribution also showed considerable differences in the deposits between the mid-crown periphery and mid-interior portion of the fir tree. Such a trend also existed in the bottom-periphery and bottom-interior levels (Table 1). However, none of these gradients was noticeable in the radial distribution of the chemical in the birch tree crown, since the deposit values were quite similar in all radial locations. The reason for these differences could be the same as those mentioned above.

Variations in the Deposits Among the Three Types of Flowers

Wide variations were observed in deposits on the simulated flowers compared to those on the live flowers (Table 2). Analysis of variance indicated no significant differences in the deposits among the three types of simulated flowers, although significant differences (ANOVA $P \leq 0.05$) were noted in those of the natural flowers, because of the small standard deviations that were observed. It appears that among the three natural flowers, the tubular chokecherry received the most deposits, while the planar strawberry received less than the chokecherry. The bell-shaped blueberry blossoms received the least deposit. The reason for these findings could be the dense packing of petals in the chokecherry flowers, which probably collected the small droplets more efficiently than the planar strawberry flowers, which in turn received more droplets than the bell-shaped blueberry flowers. On the other hand, differences in their surface properties, degradative patterns and micrometeorological factors, could also have played some role.

The Usefulness of Aluminum Surfaces for Deposit Collection in Forestry Spraying

In spite of the marked differences observed in the deposits between the simulated and natural surfaces, there was a general trend for proportional variation in the deposits; i.e., when the deposit was high on an aluminum sampler in a location, there was a corresponding high deposit on the biological sample collected from the same location. This implies that the aluminum samplers can provide a relative picture of the distribution of spray deposits in different components of the forest ecosystem, although they cannot provide a picture of the actual residues present in the biological samples.

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SONIC ANEMOMETER

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ABSTRACT – This note describes a sonic anemometer or more precisely, a sonic anemometer thermometer, that has been designed to measure accurately low air velocity in the range of 0 - 10 m/sec and the speed of sound hence air temperature. These measurements are expressed in terms of fundamental physical quantities which can be determined with a high degree of accuracy, namely length and time. Consequently this sonic anemometer can be used as a standard for low air velocity calibration.

RÉSUMÉ – Cette note décrit un anémomètre sonique ou plus précisément un anémomètre-thermomètre sonique. Cet instrument a été conçu pour mesurer avec précision des vitesses de l'air variant entre 0 et 10 m/sec et la vitesse du son dans l'air de laquelle on peut déduire la température de l'air. Ces vitesses et cette température sont obtenues en évaluant des paramètres physiques de base, longueur et temps, pour lesquelles des mesures très précises peuvent être effectuées. Ainsi, cet anémomètre sonique peut servir d'instrument-étalon pour calibrer des systèmes impliquant de très basses vitesses d'air.

The underlying principle of operation of the sonic anemometer is the measurement of the time of flight of a spark generated pressure wave. This wave travels between two identical pressure transducers characterized by a fast frequency response and which are separated by a known distance. A pressure transducer is diagrammatically shown in Figure 1.

The spark can be considered to be a point source generating a spherical pressure wave which propagates in the air with the speed of sound c. If the air moves with velocity u with respect to the array of sensors fixed in space, then it is possible to calculate the velocity of air and the speed of sound by using measurements of time of flight of the pressure wave (Refs. 1, 2 and 3).

As an example, consider a one-dimensional array consisting of a spark generator and two pairs of transducers mounted in line as shown in Figure 2. The spark generator is in the centre and one pair of transducers separated by a distance d_1 is located upwind of the spark generator and a second pair of transducers separated by a distance d_2 is located downwind, where $d_1 \cong d_2$. Let the upwind time of travel be t_1 and the downwind be t_2. Then we have:

$$\frac{d_1}{t_1} = c - u \tag{1}$$

$$\frac{d_2}{t_2} = c + u \tag{2}$$

From the Equations (1) and (2) the speed of sound c and the velocity of air u can be calculated as follows:

$$c = \frac{1}{2}\left(\frac{d_2}{t_2} + \frac{d_1}{t_1}\right) \tag{3}$$

$$u = \frac{1}{2}\left(\frac{d_2}{t_2} - \frac{d_1}{t_1}\right) \tag{4}$$

Similarly, velocities of air in other directions and the speed of sound can be obtained using a suitable transducer array. For example, the instrument developed by the Flight Research Laboratory of the National Aeronautical Establishment uses an orthogonal array consisting of six pairs of transducers and two spark sources mounted in three mutually perpendicular lines. The prototype instrument is shown in Figures 3 and 4; Figure 4 shows the instrument mounted on a meteorological tower. Figure 2 shows the part of the instrument measuring the vertical air velocity (shown in horizontal position) and Figure 5 shows the horizontal array.

The temperature is obtained from the speed of sound c using the formula for perfect gases (dry air)

$$c = K\sqrt{T} \tag{5}$$

where K is a constant and T is the absolute temperature in degrees Kelvin.

In the air the speed of sound is a function of water vapour content and can be approximated as follows (Refs. 3 and 4):

$$c^2 \cong 403T\left(1 + 0.32\,\frac{e}{P}\right) \tag{6}$$

where e is the vapour pressure and P is the atmospheric pressure. These quantities can be derived from relative humidity which must be measured independently, and then must be presented in the same units.

With each spark in the horizontal array a measurement is obtained of u and v, the air velocities in the two horizontal axes, and two corresponding measurements of the speed of sound c_u and c_v (see Fig. 5). Similarly, a vertical air velocity w and speed of sound c_w are obtained from the vertical array (see Fig. 2).

Sampling rates of 50 samples per second have been tried, but the data collected by the prototype instrument were at

12 samples per second. The sampling rate was limited by the data processing system used. The upper limit of sampling rate is dependent on the removal of ionized molecules from the spark area and will depend on air velocity. Rates faster than 50 samples per second should be possible but have not been tried.

The instantaneous measurement of c_u, c_v, c_w, u, v and w are contaminated by noise believed to be mostly Gaussian. Averaging of several readings gives results consistent to about 0.01 m/sec. Standard deviations of air velocity components are shown in Figure 6 and are typically 0.025 m/sec to 0.05 m/sec; in Figure 6 standard deviations are plotted with respect to horizontal base lines intentionally displaced to avoid crowding.

The speeds of sound c_u, c_v and c_w are plotted in Figure 7 showing excellent agreement with respect to each other and with respect to a platinum thermometer located in an aspirated probe. Note that the platinum thermometer has a much slower time response.

The temperature measurements taken with the sonic anemometer and platinum thermometer are shown in Figure 8. On the x axis we have readings from the platinum thermometer in an aspirated probe labeled "Rosemount" and on the y axis we have temperature measured with the sonic anemometer labeled "sparker".

It should be mentioned that the sonic anemometer can measure air temperature accurately and the measurements are not affected by solar radiation. The ability of measuring vertical velocity w and temperature T with the same high frequency response allows calculation of $\overline{wT}$ correlation which is a measure of heat flux and is used in the determination of atmospheric stability. The power spectral density of turbulence is shown in Figure 9. The smooth line on Figure 9 is the theoretical von Karman law. The measured data shows very good agreement with the theoretical predictions.

The calibration of the instrument is obtained by "hooding" the transducers; that is, enclosing the instrument to ensure zero air velocity. The temperature and humidity are measured in the enclosure or hood to calculate the value of the speed of sound c. Using these two values, that is, c and zero air velocity, the instrument is calibrated. The anemometer has also been calibrated in the NAE 6' X 9' wind tunnel before and after the field trials demonstrating excellent stability of the instrument. The details of the wind tunnel calibrations are described in Reference 5. The wind tunnel calibration versus angle of yaw is shown in Figure 10. The deviations from sinusoidal behaviour are caused when the axis of transducers is aligned with the direction of wind. This is to be expected. A new instrument was designed to minimize these effects.

In conclusion, the sonic anemometer developed by the Flight Research Laboratory of the National Research Council performed very well in the field and in the laboratory conditions. It measures accurately air velocity, its direction and the speed of sound; hence, air temperature. The fluctuations in air velocity can be recorded to determine the air turbulence and the spectral density of air turbulence. The temperature measurements are not subject to solar radiation and can be made with the same frequency response as the air velocity; this allows us to measure accurately $\overline{wT}$ correlation that is used in the determination of atmospheric stability.

The success of this instrument can be attributed to the use of a spark to produce a shock wave with very fast pressure rise time and to the use of transducers with high frequency response.

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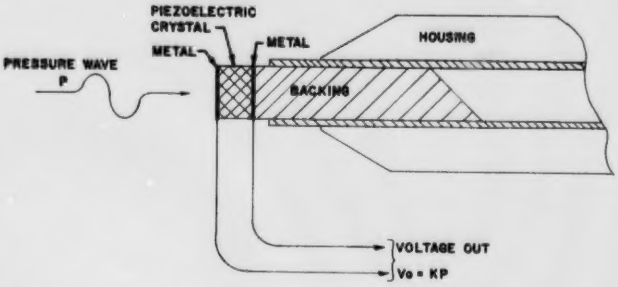
PIEZOELECTRIC CRYSTAL
METAL
METAL
HOUSING
PRESSURE WAVE P
BACKING
VOLTAGE OUT
Vo = KP

FIG. 1: PRESSURE TRANSDUCER

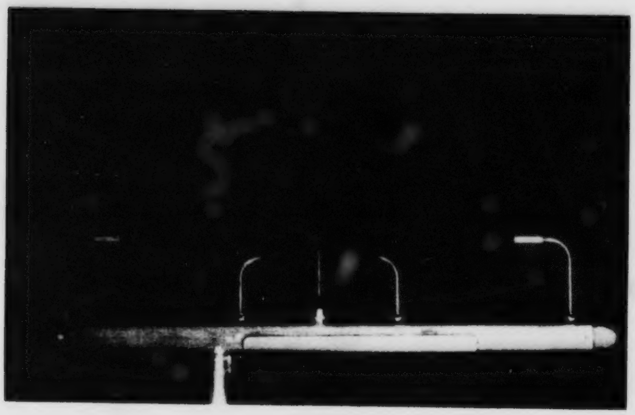

FIG. 2: ONE-DIMENSIONAL ARRAY

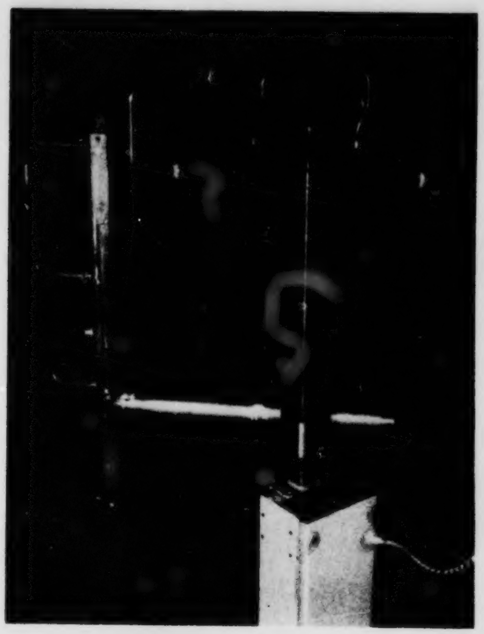

FIG. 3: SONIC ANEMOMETER

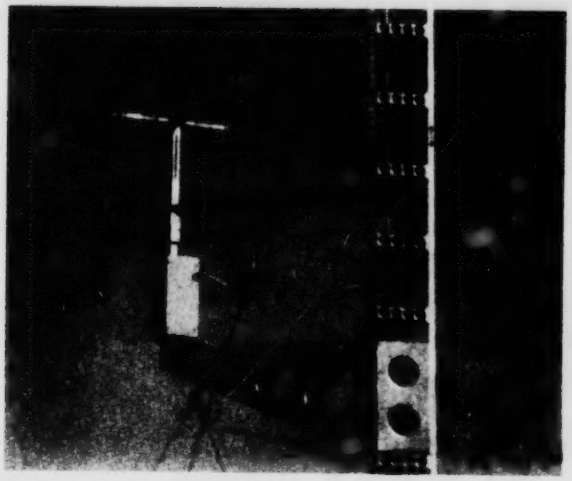

FIG. 4: SONIC ANEMOMETER ON THE METEOROLOGICAL TOWER

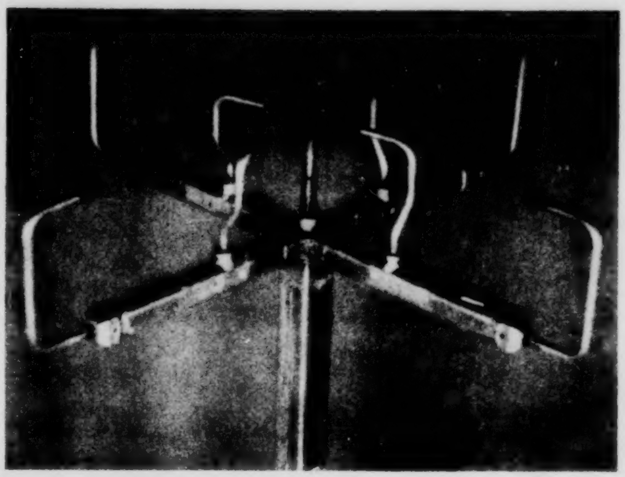

FIG. 5: HORIZONTAL ARRAY

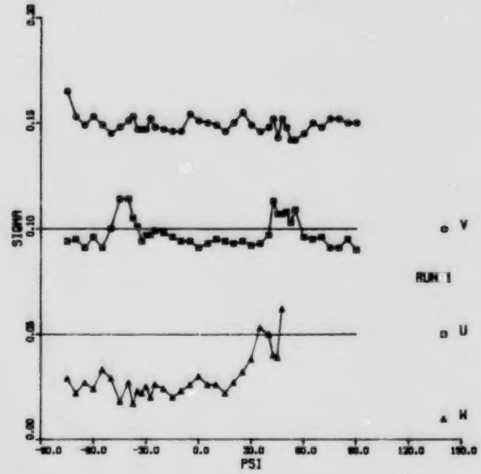

FIG. 6: STANDARD DEVIATIONS OF AIR VELOCITY COMPONENTS

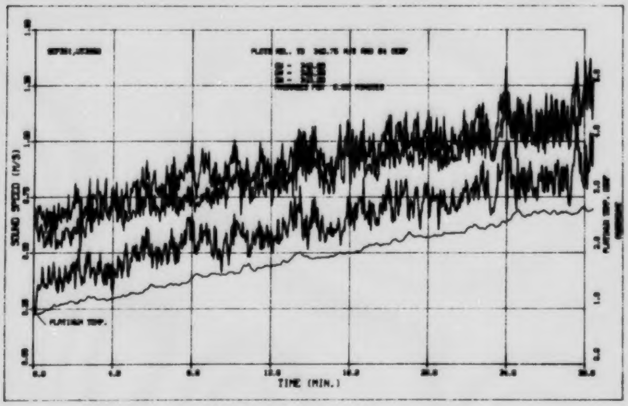

FIG. 7: SPEED OF SOUND AND REFERENCE TEMPERATURE

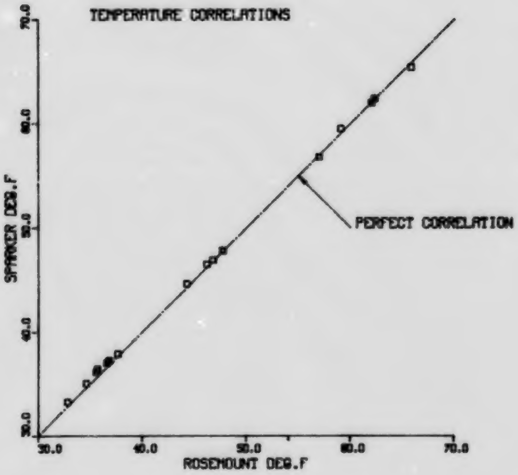

FIG. 8: CORRELATION BETWEEN TEMPERATURES MEASURED WITH SONIC ANEMOMETER AND PLATINUM THERMOMETER

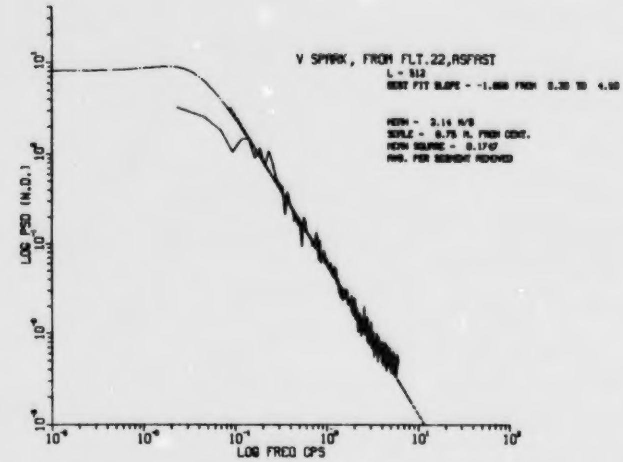

FIG. 9: POWER SPECTRAL DENSITY MEASURED WITH THE SONIC ANEMOMETER

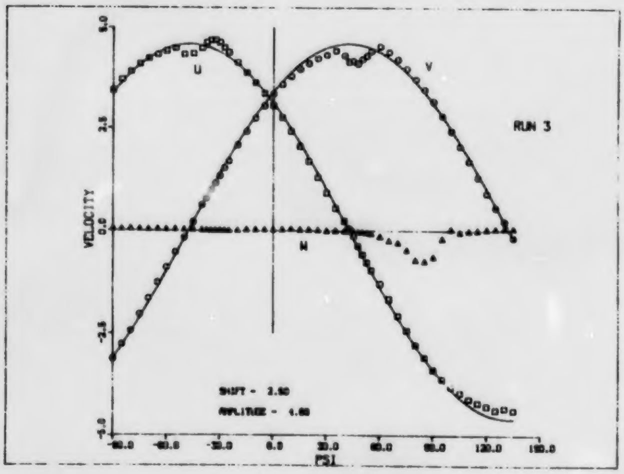

FIG. 10: WIND TUNNEL CALIBRATION, RESPONSE vs ANGLE OF YAW

AN ASSESSMENT OF THE VALUE OF AN ANGLE OF ATTACK INDICATOR TO THE AGRICULTURAL AND FORESTRY SPRAY PILOT

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ABSTRACT — One of the three major causes of accidents in agricultural and forestry aviation is inadvertent ground contact resulting from aircraft stalling or "mushing" during manoeuvres requiring high angles of attack. Typical aircraft used in these roles are not equipped with instrumentation which will directly indicate how close the aircraft is to the stall. Current high performance military aircraft, on the other hand, are equipped with angle of attack (AOA) indicators to assist the pilot in critical flight regimes and these instruments do indicate directly how close the aircraft is to the stall and therefore the amount of additional lift available.

This paper describes a research program aimed at examining the effectiveness of an AOA measuring system as a reliable indicator of the amount of reserve lift available during typical spraying manoeuvres. The AOA indicating system which is being evaluated is a commercially available, simple, non electric, self contained system which can be readily retrofitted to any typical light aircraft. The system is being evaluated to determine the effects of wing loading, side slips, roll rate, aileron or flap deflections and chord wise location of the sensing probe. Flight test results to date are presented.

RÉSUMÉ — L'écrasement de l'avion suite à un décrochage ou à un manque de puissance lors d'un vol à basse vitesse et sous un angle d'attaque élevé est une des trois causes principales d'accident en aviation agricole et forestière. D'ordinaire, les avions utilisés en agriculture et en foresterie ne sont pas équipés d'instruments indiquant l'approche des conditions de décrochage. Par ailleurs, les avions militaires à haute performance sont munis d'indicateurs d'angle d'attaque (IAA) fort utiles en régime de vol critique. Ces instruments indiquent à quel point l'avion s'approche d'une attitude de décrochage et par le fait même la marge de force de portance disponible.

Nous présentons ici un programme de recherches dont le but est d'évaluer l'efficacité d'un IAA comme indicateur de la marge de force de portance disponible lors de manoeuvres typiques des opérations d'arrosage aérien. L'IAA qui est évalué est disponible sur le marché. C'est un système simple, ne comprenant aucune composante électrique et qui s'adapte aisément à n'importe quel avion léger. Ce système est en cours d'évaluation pour déterminer l'effet de la charge ailaire, des glissements latéraux, de la déflection des ailerons et des volets, du tanguage et de la position du senseur le long de la corde de l'aile sur ses performances. Nous présentons des résultats d'essais en vol.

INTRODUCTION

One of the three major causes of accidents in agricultural and forestry aviation is aircraft stalling or mushing. Typical aircraft used in these roles are not equipped with instrumentation which will directly indicate how close the aircraft is to the stall. The Associate Committee on Agricultural and Forestry Aviation has asked the National Aeronautical Establishment's Flight Research Laboratory to evaluate angle of attack (AOA) indicators as a pilot aid in preventing agricultural and forestry aircraft stall/spin accidents. Current high performance military aircraft are equipped with AOA indicators to assist the pilot in critical flight regimes. These systems are undoubtedly successful and might well be of assistance to the spray pilot, however they are complex, expensive, require electrical power and are not a practical solution for the agricultural aircraft operator. There are currently two commercially available AOA indicating systems which are relatively inexpensive; they are the SafeFlight Angle of Attack Indicator and the Huntington Lift Reserve Indicator (LRI). The SafeFlight System is an adaption of the stall warning indicator used on many light aircraft. It is a relatively simple system but does require electrical power and therefore could not be readily installed on many of the light aircraft used by private spray operators. The Huntington LRI is self-contained and does not require electrical power unless it is being used in icing conditions. The LRI currently costs about U.S. $800.00 and presumably would be somewhat cheaper if the probe's anti-icing heater element were eliminated. It was therefore felt that the LRI warranted evaluation before evaluating or developing alternate systems.

DESCRIPTION OF THE LRI

The LRI system consists of an underwing probe, a cockpit indicator and two interconnecting tubes.

LRI Probe

The probe (Figure I) is an anodized rectangular aluminum bar attached to a 5 inch diameter plate for mounting on the under surface of the wing. The probe is attached to the plate so that its fore/aft angle may be changed. The probe has two pressure sensing ports; one on the leading edge of the bar and the other on the lower end of the bar. The top end of the probe which protrudes into the wing has adapters to connect the pressure ports to the cockpit instrument. The probe and mounting plate which weigh only 340 grams (12 ounces), would not normally require any wing structural modifications and are usually mounted as, or in lieu of, an inspection panel. Discussions with the manufacturer indicate that no supplemental type certificates are available for any aircraft installation but that the United States Federal Aviation Administration (FAA) have accepted the installation of all current units as being a "minor modification". The manufacturer's installation instructions are vague and contradictory, however it would appear that the probe should be outboard of the propeller slip stream effects, inboard of any major wing tip effects, and at approximately 25% chord.

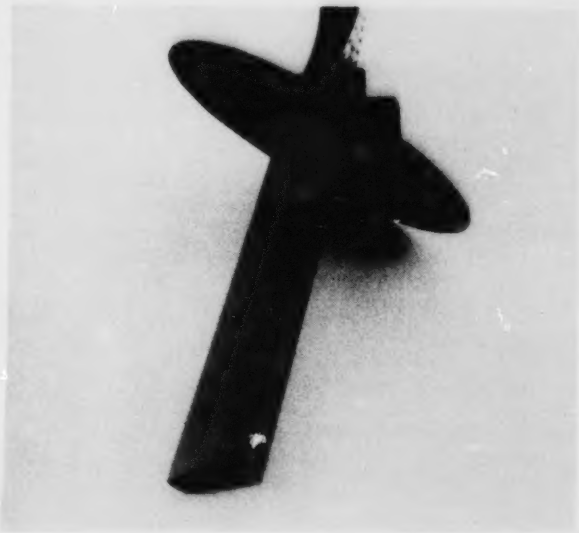

FIGURE I: LRI PROBE

Cockpit Indicator

The cockpit indicator (Figure II) is a standard 3-inch aircraft instrument. It is a differential pressure gauge and the case markings indicate that it is normally used as an airspeed indicator with a range of approximately 0-120 knots. The face of the instrument has a colour coded scale to indicate the operating regimes. It should be mounted in a position where the pilot can readily scan it while flying "heads up" (i.e. on top of the instrument panel). The indicator is connected to the probe with two ⅛" ID nylon tubes.

Installation of the LRI on the NAE Harvard Aircraft

The NAE Harvard is being used for the initial evaluation of the LRI. The Harvard's wing loading and airspeeds are similar to commercial agricultural aircraft and it can be flown to simulate typical spray aircraft manoeuvres. The LRI probe has been installed on the starboard wing at 65% semi span and 20% chord. The Harvard wing panels contain numerous spanwise "Z" sections which make it difficult to find an area large enough for the probe mounting plate without cutting any structural members. The cutout in the wing was reinforced with a doubler containing anchor nuts and the probe assembly attached as an inspection panel cover. Although the mounting location was chosen mainly on the basis of ease of installation, subsequent analysis of the flow around the Harvard wing indicates that it is a reasonable location. As the lift coefficient (C_L) increases from 0.4 (normal cruise) to C_L 1.5 (stall) the flow angle at the probe varies from −1.5° to +11°.

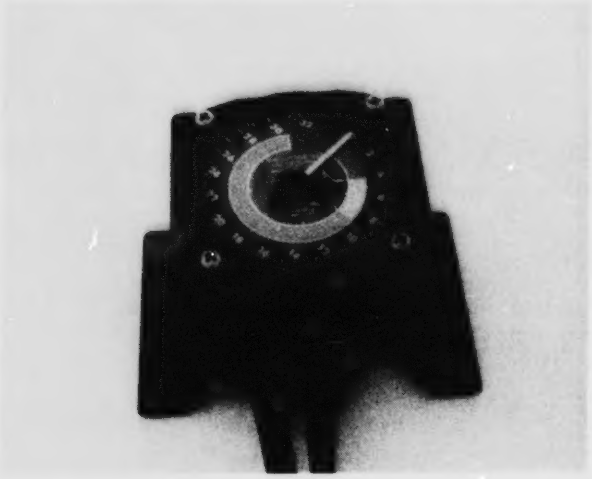

FIGURE II: LRI COCKPIT INDICATOR

The Potential Usefulness of the LRI as an AOA Indicator Based on Wind Tunnel Tests

The LRI probe, without a wing section, has been tested in the Wichita State University 7′ × 10′ low speed wind tunnel and the following observations and conclusions are based on their unpublished data.

If the LRI probe is set at 45° to the airflow (that is rotated forward 45° from the vertical as per Figure III) then the airflow will be at 45° to the local surface at each port and the differential pressure (Δp) across the ports should be zero. The wind tunnel data show that the angle of zero Δp is actually 35° and is probably due to the sharp edges on the end of the probe. This angle of zero Δp is independent of free stream dynamic pressure (q). At any angle above or below 35° Δp (and the meter reading) is a function of both AOA (α) and free stream dynamic pressure (i.e. $\Delta p = q.\Delta\alpha$). This indicates that the LRI cannot be used to directly indicate AOA. This does not necessarily eliminate the LRI as a useful aid to the spray pilot since the spray pilot is not interested in his actual AOA; instead he is interested in one specific angle of attack (the stall angle) and how close he is to that point. Since the LRI will indicate one particular angle of attack without Δp or q effects the probe could presumably be set to give this indication at the stall angle. At any AOA above or below this point the LRI indication will be a function of $q.\Delta\alpha$ and since $\Delta L = K.q.\Delta\alpha$ (where K is a constant for a particular aircraft) the LRI indication will be the amount of additional lift available to the pilot at that airspeed (or q). This is of more value to the spray pilot than the actual AOA or $\Delta\alpha$ to the stall. It should be noted that the above discussion is for the LRI probe in a free stream flow and does not consider wing effects.

The wind tunnel test also simulated side slip angles up to 20°. Side slip angles of up to 15° have a negligible effect on the results for the range of AOA from cruise to stall.

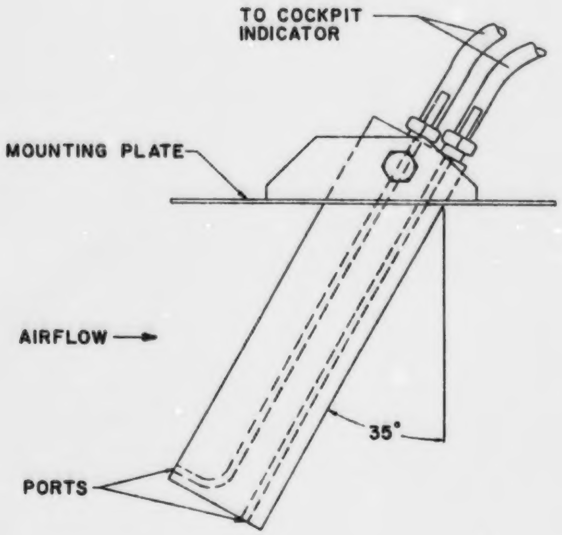

FIGURE III: LRI PROBE DRAWING

The above discussion has shown the limitations of the LRI as an AOA indicator. It should be noted that the manufacturer does not advertise it as being a conventional AOA indicator but instead calls it a Lift Reserve Indicator the implication of which is in keeping with the preceding discussion.

In Flight Evaluation of the LRI

For test purposes the face of the LRI indicator has been modified to include a numbered scale. It is numbered from 0 to 32 with zero Δp being "O" and each scale unit representing 10° of meter movement (i.e. 32 = 320° of needle rotation).

The initial flight trials indicated that in level cruise flight the LRI readings increased rapidly as airspeed increased; an LRI reading of 32 was obtained at an indicated airspeed (IAS) of 140 knots. One g stalls at 55 kts IAS yielded LRI readings of 3. Stalls at higher IAS were induced by turning at various bank angles and pulling g to increase the effective wing loading (effective wing loading = g × wing loading). As g and IAS were increased to 3 g and 110 kts respectively the LRI readings increased to 11. The pilots' post flight comments confirmed the test results that the LRI was not significantly better than the airspeed indicator at predicting the stall.

For the second set of tests the LRI probe was rotated forward approximately 2 degrees and the previous tests repeated. The results of the cruise flight and one g stall tests were approximately the same as the initial tests; however in subsequent stalls as g and IAS were increased to 3 g and 110 kts respectively the LRI readings only increased to 7. The test data showed a significant improvement in the LRI's ability to indicate an approaching stall and the pilots' post flight comments indicated that they found the LRI considerably superior to the ASI in indicating the proximity of a stall. In Figure IV the LRI readings and the IAS at the stall have been plotted against the effective wing loading. The data shows that as expected the IAS stall readings increased significantly with increasing effective wing loading while the LRI stall readings increased only slightly.

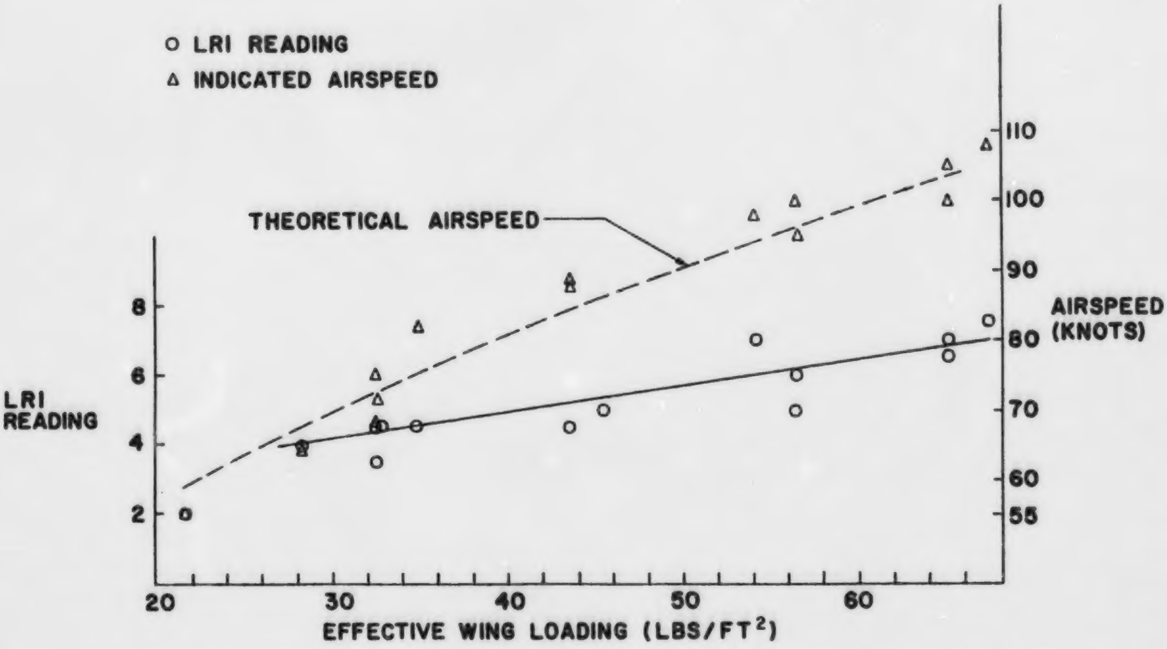

FIGURE IV: AIRSPEED AND LRI READINGS vs EFFECTIVE WING LOADING AT THE STALL

For the third set of flight trials the LRI probe was rotated forward an additional two degrees and the previous test program repeated. No significant change in the level cruise flight data was noted. In the stall tests the one g (55 kt) stall gave an LRI reading of +2 and as g and airspeed were increased to 3 and 110 kts respectively the LRI readings decreased to −1.

In all three sets of flight trials the stalls were carried out in both left and right turns without any significant difference in the test data.

CONCLUSIONS

Test flights to date indicate that the LRI is significantly better than an airspeed indicator at predicting the stall with varying effective wing loading.

Flight Tests 2 and 3 indicate that there is an optimum probe angle between settings 2 and 3 where the stall would probably give a single LRI reading irrespective of effective wing loading.

Flight Tests with the LRI should be continued to:

(1) optimize the probe setting;

(2) determine whether or not the LRI system lag is significant;

(3) simulate the manoeuvres frequently used by spray pilots with induced stalls to determine the LRI's responses in these regimes; and,

(4) determine if the LRI can be used to establish best rate of climb, glide angle, etc.

This continued flight test program would determine if the program should be extended to evaluate or develop other types of AOA systems or if the LRI adequately meets the needs of the agricultural and forestry pilot.

INFLUENCE OF SMALL DROPLETS ON HERBICIDE TOXICITY

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ABSTRACT — A monosize droplet generator that produces single uniform droplets was used in the laboratory to demonstrate that small droplets (150 to 350 µm) of three herbicides (glyphosate, hexazinone and triclopyr) were more toxic to white birch *Betula papyrifera* L. than large droplets (450 to 650 µm). Toxicity of small droplets was related to dosage, treated leaf area plus penetration and translocation of the pesticide. Age of leaf, spray concentration and multi-sized droplets did not significantly influence toxicity; however very high herbicide concentration nullifies any advantages small droplets may have on efficacy. These findings are discussed in relation to practical herbicide uses.

RÉSUMÉ — Un générateur de gouttelettes monotaille qui produit des gouttelettes individuelles de taille uniforme, a été utilisé au laboratoire pour montrer que les petites gouttelettes (150 à 350 µm) de trois herbicides (glyphosate, hexazinone et triclopyr) étaient plus toxiques pour le bouleau à papier, *Betula papyrifera* L., que les gouttelettes plus grosses (450 à 650 µm). La toxicité des petites gouttelettes était liée à la dose, à la surface foliaire traitée ainsi qu'à la pénétration et au déplacement du pesticide. L'âge de la feuille, la concentration du produit pulvérisé et la présence de gouttelettes de tailles multiples n'influaient pas de façon significative sur la toxicité; toutefois, une concentration d'herbicide très élevée annulait tout effet positif que les petites gouttelettes pourraient avoir sur l'efficacité. On discute de ces constatations dans le contexte des [illegible] pratiques des herbicides.

INTRODUCTION

There is general disagreement among researchers in regard to the role of size, density and composition of herbicide spray droplets on efficacy and crop tolerance. Ennis and Williamson (1963), McKinlay et al. (1972), Ambach and Ashford (1987), Prasad (1985) and Rogers and Kirkland (1985) reported that small droplets are more efficacious than large droplets primarily because they provide better coverage (more can be atomized from a given volume) and demonstrate greater penetration and translocation than larger ones. Other researchers (Smith 1946, Barzee and Stroube 1972, Maybank 1981, Grover et al. 1985 and Barry 1985) believe that smaller drops are undesirable because they are prone to drift which potentially reduces the active ingredient (AI) in the target area while adding to pollution of off-target areas. Finally, there is yet another school of thought (Mullison 1953, Ayres et al. 1984, Gebhardt 1986) which supports the theory that droplet size has no undue influence on weed control under field conditions.

Clearly there is an urgent need for research so that the practitioner can decide what type of herbicide spray would confer maximum efficacy and crop tolerance while minimizing operational costs and environmental impact.

The objectives of this study were i) to determine under controlled laboratory conditions the role of various sizes of three herbicide droplets on their toxicity to a common forestry weed, and ii) to investigate some factors such as spray concentration (i.e. application volume/dosage rate), age of leaves and multi-size spray droplets that may modify the phytotoxicity of herbicide sprays.

MATERIALS & METHODS

Culture of Plants

White birch (*Betula papyrifera* L.) seeds were germinated in sterilized soil kept at 20°C. When one month old, the seedlings were transplanted into individual pots (15 × 15 × 10 cm) filled with sterilized soil and grown in a greenhouse under controlled conditions [temperature 20 ± 1°C; light-regime 2000 lux with a 16 : 8h, (light : darkness); and a RH of 70 ± 15%]. Seedlings at the 6-8 leaf stage (4 months old) were used as test plants.

For testing crop tolerance we used 4-year old white spruce seedlings *Picea glauca* (Moench) Voss that were kept in cold storage and removed, flushed and hardened only when required.

Droplet Production

Single monosize droplets in four basic sizes (150, 350, 450 and 650 µm diameters) were produced using a droplet generator (Fig. 1a) which was built on principles developed by Rayner & Haliburton (1955) (B. Cadogan unpublished data). The device employs a constant flow (2 µ l/min) of the pesticide solution that is pumped through a needle (1D:0004 mm) to form a pendant drop. A spinning disc, with a sharp blade attached, rotating vertically at a constant speed, used the blade to remove a single droplet from the pendant drop at each revolution. Once the constant flow volume equals the volume that is excised as droplets, the droplets are monosized. To achieve different monosized droplets requires varying the flow rate, the disc's rotational speed and sometimes the attached blade. Generally the smaller drops required a very fine needle as the attached blade. To confirm that the aerodynamic droplets were indeed monosized and were numerically matched with the known RPM of the disc, the drops were caught on kromekote cards Fig. 2 and the stains counted and measured. Stains from a wide range of known aerodynamic droplets showed a linear relation between stains and droplets. (Fig. 3)

FIGURE 1A: PHOTOGRAPH OF THE MONOSIZE DROPLET GENERATOR SHOWING THE METHOD OF PRODUCTION OF UNIFORM AND HOMOGENEOUS DROPLETS.

Treatment of Plants

Birch seedlings in the 6-8 leaf stage were used to study herbicide treatments. Except for the areas designated for treatment, the entire plant and soil were covered with a plastic sheet (Saran Wrap, Union Carbide, Tor.). Generally, one fully expanded 3rd leaf, and only this leaf unless otherwise stated, was chosen to be treated. The plants were then placed in an enclosed plexiglass chamber (Fig. 1b) to minimize inflight evaporation of the drops, and to allow drops emitted by the droplet generator to impact accurately on the target leaf. As the glyphosate formulation contained a tracer dye (Rhodamine 'B' dye 0.1% v/v) the drops could be clearly seen and counted; but most importantly, care was taken to ensure that the drops were distributed uniformly on the leaf's lamina. In some tests more than one leaf was treated.

FIGURE 1B: A VIEW OF THE TREATMENT CHAMBER AND PLASTIC ENCLOSURE WHERE DROPLETS WERE PRODUCED AND DEPOSITED ON THE TARGET LEAF.

Three commercial formulations, glyphosate, hexazinone and triclopyr (Monsanto Co., MO U.S.A.; EI Dupont & Co., Delaware U.S.A.; Dow Chemical Co., Mich. U.S.A.) were used in this research. We studied the effects of droplet sizes using all three herbicides and then resorted to the detailed studies with glyphosate. Except as otherwise stated, test solutions of each herbicide were prepared at 2.0 kg/80 l water and 2.0 μl of each solution applied to the plant as different sized drops.

After treatment the drops were allowed to dry on the leaf surface, the plastic was removed and the plants were moved to a greenhouse where they were observed for 6 weeks.

Measurement of Responses

Phytotoxicity was measured by assessing and scoring the damage to the treated leaf (TL) and the untreated parts (UP) using a scale 0 to 100%. Translocation of the herbicides was assessed by the degree of damage to or symptoms seen in the actively growing untreated parts of the plant (ie. young leaves, shoots and apical buds). The three herbicides elicited a variety of plant responses (necrosis, epinasty, chlorosis etc.), therefore, we allowed three weeks for these responses to stabilize and assessments were conducted weekly for 6 weeks. In some cases the magnitude of necrosis required estimates with the aid of a planimeter.

Statistical Analysis

Analysis of variance (ANOVA) and Duncan's Multiple Range Test (DMRT) (Duncan 1955) were employed to detect real differences between phytotoxic responses produced by the treatments. Where necessary, the percentages were transformed using arc sin (Snedcor 1957).

RESULTS AND DISCUSSION

Effect of Droplet Sizes

Table 1 presents data relating to the phytotoxic responses of white birch after treatment with four droplet sizes of hexazinone, triclopyr and glyphosate. Considering that the treatments were equal in volume, the data show quite clearly that phytotoxicity of the treated leaf is inversely related to droplet size i.e. small drops are more toxic than larger ones. Where substantial translocation of chemical occurred (eg. triclopyr) as evidenced, for example, by the degree of toxicity to the untreated parts (U.P.), small droplets did not induce significantly (=0.05) more toxicity than larger ones; but where the herbicide (eg. hexazinone and glyphosate) did not show extensive translocation, smaller droplets seemed to cause more epinasty and damage to U.P. than larger drops.

Influence of Droplet Concentration

Data in Table 2 show that when the concentration of the spray medium increases, the advantages that small drops seem to have are reduced. When glyphosate is applied at 4.0 kg/80 l water in place of 1.0 kg/80 l water, a few (17) large (627 μm) concentrated drops were as phytotoxic as 930 small 179 μm) drops whether they be diluted or concentrated. It appears therefore that if the small drops become too dilute, a small number of large concentrated drops might be more toxic, but high dosage applications

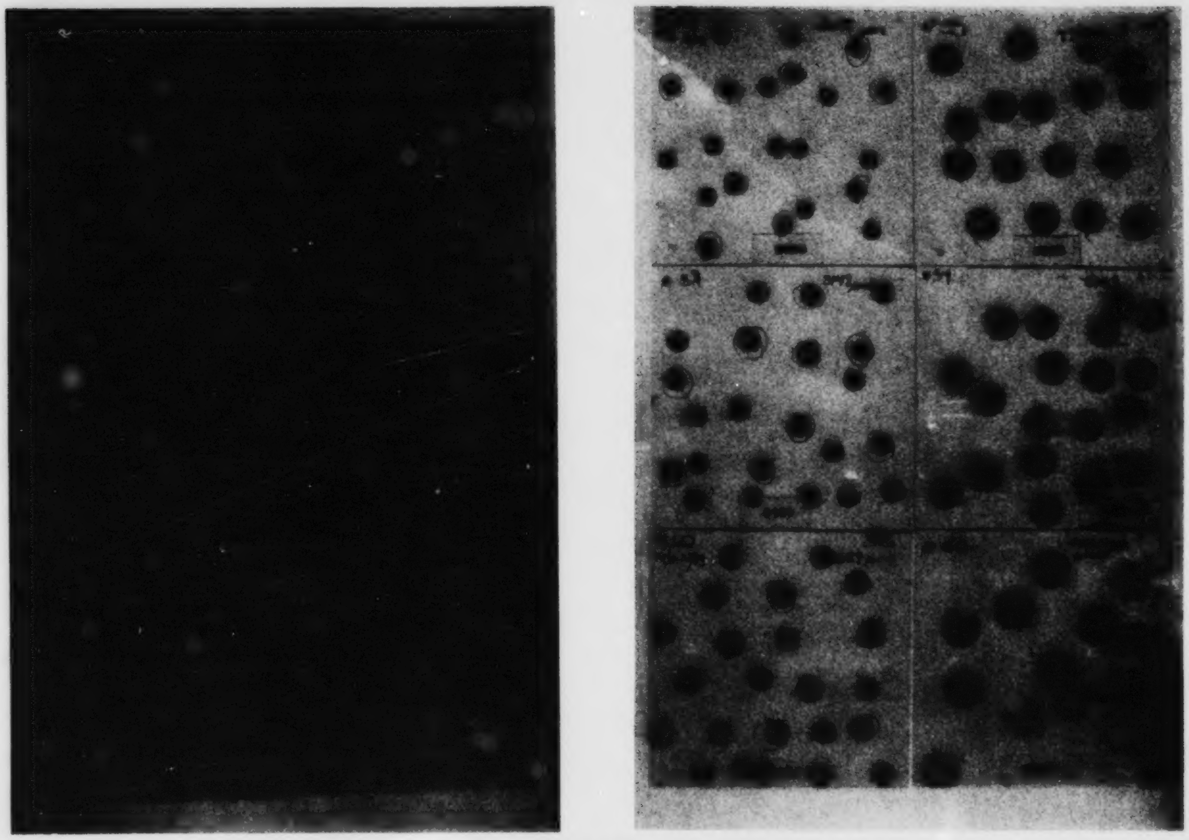

FIGURE 2: SPECTRA OF MONOSIZE AND UNIFORM DROPLETS

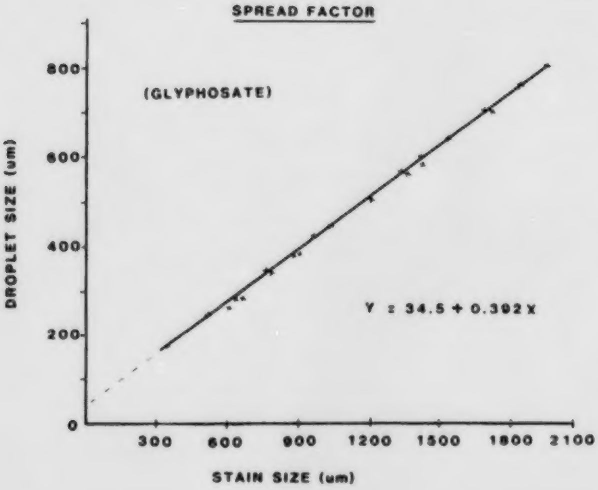

FIGURE 3: CALCULATION OF SPREAD FACTOR OF GLYPHOSATE DROPLETS ON A KROMEKOTE CARD.

TABLE 1: Effects of droplet size on three herbicides' toxicity to white birch.

Drop Size (μm)	No. of drops/ leaf[1]	% Phytotoxicity 3 weeks[2] TL	% Phytotoxicity 3 weeks[2] Up	% Phytotoxicity 6 weeks[2] TL[3]	% Phytotoxicity 6 weeks[2] Up[3]
glyphosate					
159	967	75 a	13 a	89 a	23 a
332	103	65 ab	8 ab	68 ab	22 a
447	51	67 ab	5 b	71 a	15 b
575	16	52 b	6 b	60 b	15 b
hexazinone					
159	968	88 a	0	98 a	5
315	133	74 a	0	91 ab	0
461	35	64 b	0	86 ab	0
665	17	61 b	0	70 b	0
triclopyr					
159	962	52 a	38 a	87 a	48 a
336	104	41 a	35 a	98 a	49 a
423	51	38 ab	39 a	91 a	42 a
622	16	32 b	35 a	76 b	45 a

[1] One leaf treated using 2 μl. Concentration 2.0 kg/80 l water.

[2] Each treatment analyzed separately.

[3] UP-TL-Untreated Parts and Treated Leaf. Means for the same column followed by the same letter are not significantly different (=0.05) DMRT.

are expensive and, generally, undesirable. However, at three given concentrations and one applied volume, small drops generally appear to be more advantageous than larger ones. These data suggest that on a practical level, as much, if not more attention should be paid to the concentration of the spray medium (AI/1 of medium) rather than to the dosage (AI/ha).

TABLE 2: Influence of different concentrations of glyphosate droplets on the herbicide's toxicity to white birch.

Drop Size (µm)	No. of drops/ leaf[1]	Herbicide Concentration (kg/80 l water)	% Phytotoxicity[2]	
			TL	UP
179	930	1.0	53 b	10.0 c
627	17	1.0	17 c	6.5 c
179	930	2.0	84 a	18.5 d
627	17	2.0	52 b	11.5 c
179	930	4.0	98 a	35.5 b
627	17	4.0	96 a	49.0 a

[1] One leaf treated with 2.0 µl.

[2] Assessed at 3 weeks. TL, UP denote treated leaf & untreated parts respectively. Means in each column followed by the same letter are not significantly different (=0.05). DMRT.

Influence of Leaf-age

Results presented in Table 3 demonstrate that the small glyphosate drops were more toxic than large ones regardless of leaf-age. When young leaves were treated with small (161 µm) drops, the contact (TL) and translocated (UP) phytotoxicities exceeded 90%. When young leaves were treated with large (600 µm) drops, phytotoxicity due to contact and translocated modes were significantly (=0.05) less than those observed in the plants treated with small droplets. Old leaves treated with small drops exhibited 95% contact toxicity but injury to UP was only 18%. Similarly, when old leaves were treated with large drops no translocation of the chemical occurred and contact toxicity was not significantly different from that seen when young leaves were treated with large drops. It thus appears that on a wide range of foliar ages, small droplets are more efficacious than larger droplets.

TABLE 3: Influence of 'age of leaf' on the toxicity of glyphosate sprayed in two droplet sizes

Drop Size (µm)	No. of drops/ leaf[1]	Leaf age	% Phytotoxicity	
			TL[2]	UP[2]
161	962	Young	95 a	90 a
600	17	Young	67 b	36 b
161	962	Old	99 a	18 c
600	17	Old	72 b	0 d

[1] One leaf treated with 2.0 µl. Solution concentration = 2.0 kg/80 l water.

[2] TL, UP — Treated leaf and untreated parts respectively. Assessed at 6 weeks. Means in the same column followed by the same letter are not significantly different (=0.05). DMRT.

Effects of Mixing Droplet Sizes

In this experiment, two leaves were treated in order to accommodate the large number of droplets involved. Table 4 shows that neither the mixture of small and large glyphosate drops nor large drops alone were as toxic to white birch as small drops. Because the assessment was done at 3 weeks, these figures might be conservative. The increased phytotoxicity to UP seen in the treatments with the mixture and with large droplets (refer to Table 4) might be due to the increase (4.0 µl/plant) of herbicide that was applied. Because commercial sprayers emit sprays usually with a spectrum of drop sizes, the data suggest that the practitioner should strive to employ a spray that is made up mainly of small drops.

TABLE 4: Effect of a mixture of droplet sizes on the toxicity of glyphosate to white birch.

Droplet Size (µ)	No. of drops[1]	% Phytotoxicity	
		TL[2]	UP[2]
161	1924 (962 + 962)	79 a	75 a
161 + 680	962 + 17	52 b	59 b
680	34 (17 + 17)	55 b	62 b

[1] Applied to two leaves. 4.0 µl applied and the solution was 2.0 kg/80 l water.

[2] TL, UP denote treated leaf and untreated parts respectively. Assessed at 3 weeks. Means in the same column followed by the same letter are not significantly different [=0.05]. DMRT.

Influence of Dosage and Treated Leaf-area

Increasing the dosage and the surface area that is treated with glyphosate did not change the pattern of the herbicide's toxicity to write birch (Table 5). Small drops still appeared to be more efficacious than larger ones. However, as Table 5 indicates, when the area that is treated and dosages are increased, toxicity to UP due to translocation of the herbicide also increases. Based on data shown in Table 4, the levels of injury observed when 3 leaves are treated (Table 5) were not significantly different from what was expected. The data suggest that as the number of leaves that are exposed increase, greater translocation of glyphosate would occur in birch. This increased exposure implies increased application volumetric dosage.

TABLE 5: Influence of dosage and 'area of leaf that is treated' on glyphosate's toxicity to white birch.

Droplet Size (µm)	No. of drops/ leaf[1]	Leaves treated	% Phytotoxicity[2]			
			Expected[3]		Observed	
			TL	UP	TL	UP
179	930	3	90	90	80 a	90 a
660	17	3	75	100	51 b	85 a

[1] 2.0 µl applied to each leaf. Concentration of material was 2.0 kg/80 l water.

[2] Evaluated at 3 weeks. TL, UP denote 'treated leaf' and 'untreated parts' respectively.

[3] Extrapolated from tables 1, 3 & 4.

Means followed by the same letter are not significantly different (=0.05)

The results from this research support the hypothesis that 'small' herbicide drops are more toxic to broadleaf plants than 'large' drops. The authors readily acknowledge that 'small' and 'large' droplets are relative terms and that in some applications viz insecticides, 170 µm drops could be considered 'large'. Nevertheless, in current herbicide practices, droplets >1000 µm are desirable, primarily, because a major objective in aerial application of herbicides is to avoid drift. Thus, in circumstances where drops 700-1000 µm are normal, drops of 170 µm in diameter could be accurately labelled 'small'. In this connection, neither small nor large droplets were found toxic to hardened spruce needles in the greenhouse.

These findings should provide practical information which can be applied in weed or brush control. Some pertinent conclusions are:

1) The spray concentration (AI/1 of spray medium) is of paramount importance in determining the effectiveness of drops and that in highly concentrated sprays a few 'large' drops could also be as phytotoxic as a high number of small ones. However, high concentration implies low volumes and low volumes imply small drops for good coverage.

2) Age of treated leaves does not have a direct effect on contact phytotoxicity but it does influence glyphosate's toxicity by translocating more material to growing parts. The herbicide is thus, more toxic to young leaves and buds when applied in smaller droplets.

3) Monosized small drops are more phytotoxic than a mixture of small and large ones or monosized large ones.

4) Increasing the number of leaves that are treated and the dosage improves the efficacy of the treatment.

These conclusions imply that thorough coverage of weeds is an absolute necessity if optimum phytotoxicity is to achieved. Thus, as a practice, the atomization of large drops is at a numerical disadvantage for achieving thorough coverage, as the number of drops which can be made from a given volume of liquid varies inversely as the cube of droplet diameter (Joyce 1969).

Finally, field research is required to corroborate these findings and to better elucidate the limits of effectiveness of small drops.

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DISTRIBUTION OF *BT* DEPOSIT AT SELECTED VERTICAL STRATA WITHIN A HARDWOOD FOREST

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ABSTRACT — *Bacillus thuringiensis (Bt)* was applied at 7.0 l/ha (96 oz/acre) and 30 BIU/ha (12 BIU/acre) using a Bell 47 equipped with 22-8003 flat fan Teejet nozzles directed 45° forward. Spray deposit was collected at seven vertical locations (i.e. strata 1, 24.4 m (80 ft); strata 7, ground) within a deciduous forest. In 1984, *Bt* was applied at three biological timings (zero, 20% and 75% red oak leaf expansion). In general, the volume median diameter (VMD) of spray droplets did not vary as much as drop density (drops/cm^2) among strata and trials within a timing.

RÉSUMÉ — On a effectué un traitement au *Bacillus thuringiensis (Bt)* à raison de 7,01 L/ha (96 oz/acre) et de 30 UBI/ha (12 UBI/acre) au moyen d'un appareil Bell 47 muni de buses Teejet 22-8003 à orifices aplatis, orientés à 45° vers l'avant. Le dépôt a été prélevé en sept points alignés verticalement [c'est-à-dire, strate 1, à 24,4 m (80 pi); strate 7, niveau du sol], au sein d'une forêt de feuillus. En 1984, le traitement au *Bt* a été effectué à trois "étapes biologiques" (zéro, 20 % et 75 % de l'expansion des feuilles du chêne rouge). En général, le diamètre médian en volume (DMV) des gouttelettes pulvérisées ne variait pas autant que la densité de gouttelettes (gouttes/cm^2) d'une strate à l'autre et d'un essai à l'autre pour une étape biologique donnée.

In the last 5 years, there has been a general increase in the use of aerial application of the microbial insecticide *Bacillus thuringiensis (Bt)* to suppress forest insects. For cooperative Federal/State gypsy moth, *Lymantria dispar*, suppression programs conducted in the Northeastern United States, there has been an opposing trend: in 1980, *Bt* comprised about 70% of the total program while in 1986, only about 35%. Apparently, *Bt* was not providing consistent levels of gypsy moth larval reduction and results were often inconclusive.

The objectives of this study were: (1) to quantify the *Bt* spray deposit (VMD, drops/cm^2) available at selected vertical strata within a deciduous forest for various degrees of leaf expansion, and (2) to use these field collected data to update the Forest Service Cramer Barry Grimm (FSCBG) computer program (Dumbald 1980) for deciduous forests.

MATERIALS AND METHODS

The study was conducted in a 1.6 ha (4-acre) portion of a 30 ha (50-acre) woodlot at Gettysburg National Military Park in southern Pennsylvania. The species composition of the woodlot was approximately 90% oak, *Quercus* spp., with an average height of 24.4 m (80 ft), basal area of 32.5 sq m/ha (142 sq ft/acre) and a stocking density of 132 stems/ha (52 stems/acre) and 1820 stems/ha (743 stems/acre) for the overstory and understory, respectively. There were twenty sample points randomly located within the woodlot; at each sample point, two vertical lines, 2.7 m (9 ft) apart, were attached from the ground through the overstory. There were seven sampler locations (strata) on each line corresponding to 24.4 m (80 ft) (strata 1), 15.2 m (50 ft) (strata 2), 13.7 m, (45 ft) (strata 3), 12.2 m (40 ft) (strata 4), 10.7 m (35 ft) (strata 5), 7.6 m (25 ft) (strata 6) and ground (strata 7). The samplers consisted of 10.2 × 15.2 cm (4" × 6") Kromekote cards cut into the general shape of a 75% expanded red oak leaf with one sampler at each location on each line.

Bt (Dipel 6L formulation) was applied at 7.0 l/ha (96 oz/acre) and 30 BIU/ha (12 BIU/acre) using a Bell 47 equipped with 22-8003 flat fan Teejet nozzles directed 45° forward. There were 5 aircraft swaths (22.9 m (75 ft.) intervals) needed to cover the area and helium filled balloons located at opposing sides of the woodlot were used to mark flight lines. A tracer (Red Powder 40) was added at the rate of 1 lb per 100 gallons of the tank mix to ensure readability of drops using a Quantimet 900 Image Analyzer. Spread factors were determined by Yates using the technique as described by May (1950) and wind tunnel tests were conducted to determine the droplet spectrum. The deposit within each of two 6.2 sq cm areas were read and the droplet diameters calculated from the stain diameters using the Automatic Spot Counter and Sizer computer program (Coburn 1964).

Application timings of *Bt* (i.e. runs) were designated corresponding to zero (run 1), 20% (run 2), and 75% (run 3) red oak leaf expansion. Trials were conducted within each run during the morning from 6:30 AM (trial 1), 8:00 AM (trial 2), 9:00 AM (trial 3); until 10:30AM (trial 4). Meteorological conditions were monitored at ground level and at approximately 5 m (15 ft) above the canopy.

RESULTS AND CONCLUSIONS

Data were recorded separately for each sampler location on each of two vertical lines at a sample point, summed and a mean calculated to represent that sampler location and sample point.

Run 1 was conducted without any foliage expansion on the overstory or understory trees. The mean volume median diameter (VMD) of the *Bt* spray deposit did not vary significantly ($\alpha = .05$) among trials (Table 1) nor strata within the run (Table 2). The mean droplet density (drops/cm^2) was different among trials within a run (trial 4 had significantly fewer drops than trials 1, 2 or 3) (Table 1), and among strata within the run. For all trials within the run, the mean drops/cm^2 ($\bar{x} \pm$ SE) for strata 1 was 7.68 ± 0.59 and for strata 7, 3.85 ± 0.30 (Table 3).

TABLE 1: Droplet density (drops/cm^2) and volume median diameter (VMD) of *Bt* spray droplets (expressed as X ± SE) recovered for three application timings, Gettysburg, Pennsylvania – 1984.

Application Timings		Trials (Time of Day)			
		Trial 1 (6:00AM)	Trial 2 (7:30AM)	Trial 3 (9:00AM)	Trial 4 (10:30AM)
Run 1 (zero)	drops/cm^2	6.91 ± 0.34	8.84 ± 0.35	4.39 ± 0.22	2.18 ± 0.12
	VMD	193.49 ± 2.14	189.79 ± 1.95	196.34 ± 2.94	206.59 ± 3.11
Run 2 (20%)	drops/cm^2	17.44 ± 0.59	14.10 ± 0.57		
	VMD	190.99 ± 3.08	187.96 ± 2.39		
Run 3 (75%)	drops/cm^2	4.56 ± 0.30	4.02 ± 0.29	2.81 ± 0.16	
	VMD	164.94 ± 3.17	158.30 ± 2.99	152.22 ± 3.30	

TABLE 2: Volume median diameter (VMD) of *Bt* spray droplets (expressed as x ± SE) recovered at various vertical strata within a deciduous forest, Gettysburg, Pennsylvania – 1984.

		Application Timing (Percent Red Oak Leaf Expansion)			
Strata	Height (ft)	Run 1 (zero)	Run 2 (20%)	Run 3 (75%)	All Runs Combined
1	80	190.45 ± 4.17	182.74 ± 5.70	166.34 ± 5.14	180.83 ± 2.93
2	50	192.60 ± 3.08	182.50 ± 4.65	162.60 ± 4.30	180.19 ± 2.44
3	45	196.66 ± 3.27	191.35 ± 4.96	162.06 ± 4.67	183.76 ± 2.66
4	40	195.47 ± 3.21	189.30 ± 4.95	153.67 ± 4.52	169.94 ± 2.74
5	35	195.01 ± 3.10	188.86 ± 5.11	157.91 ± 4.70	181.08 ± 2.68
6	25	198.34 ± 3.45	195.20 ± 5.34	158.71 ± 4.90	184.22 ± 2.88
7	0	206.44 ± 3.91	195.07 ± 5.11	149.29 ± 5.60	184.50 ± 3.40

TABLE 3: Droplet density (drops/cm^2) of *Bt* spray deposits (expressed as x ± SE) recovered at various vertical strata within a deciduous forest, Gettysburg, Pennsylvania – 1984.

		Application Timing (Percent Red Oak Leaf Expansion) Individual Runs			
Strata	Height (ft)	Run 1 (zero)	Run 2 (20%)	Run 3 (75%)	All Runs Combined
1	80	7.68 ± 0.59	20.26 ± 1.22	4.56 ± 0.38	9.41 ± 0.62
2	50	6.26 ± 0.51	19.61 ± 1.07	4.90 ± 0.48	8.68 ± 0.56
3	45	6.01 ± 0.48	18.46 ± 0.99	4.86 ± 0.52	8.36 ± 0.54
4	40	5.48 ± 0.41	16.77 ± 0.86	4.15 ± 0.42	7.52 ± 0.48
5	35	5.40 ± 0.43	14.91 ± 0.86	3.70 ± 0.35	6.90 ± 0.44
6	25	4.61 ± 0.38	12.49 ± 0.80	2.94 ± 0.21	5.78 ± 0.37
7	0	3.85 ± 0.30	8.05 ± 0.53	1.58 ± 0.10	3.98 ± 0.25

Run 2 was conducted with approximately 20% red oak leaf expansion (i.e. 10% white oak expansion). The mean VMD did not vary significantly among trials (Table 1) nor strata (Table 2); whereas the drops/cm^2 varied among strata. For all trials within run 2, the mean drops/cm^2 for strata 1 was 20.26 ± 1.22 and for strata 7, 8.05 ± 0.53 (Table 3).

Run 3 was conducted with approximately 75% red oak leaf expansion. The VMD did not vary significantly among trials (Table 1) nor strata (Table 2); whereas the drops/cm^2 varied significantly among strata (Table 3).

When drops/cm^2 data for all trials and runs were averaged for strata there was a significant decrease from strata 1 to strata 7 (Table 3). A similar significant decrease in drops/cm^2 from strata 1 to strata 7 for all trials within a run (Table 3) was evident, but due to a trial/strata interaction the pattern varied from trial to trial within and among runs. Therefore, individual trials within a run were not necessarily representative of the overall pattern (i.e. to predict drops/cm^2 at each strata you need to know the associated meteorology). The drops/cm^2 data for all strata and runs by trial were: Trial 1, 9.46 ± 0.37; Trial 2, 9.00 ± 0.32; Trial 3, 3.60 ± 0.15 and Trial 4, 2.18 ± 0.12.

In general, the volume median diameter (VMD) of spray droplets recovered on the samplers did not vary significantly among strata within a run. The drop density (drops/cm^2) decreased among strata (i.e. greater numbers of drops/cm^2 recovered at strata 1 than strata 7).

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AERIAL APPLICATION METHODS USED IN SOUTHERN PINE SEED ORCHARDS

Larry R. Barber[1] and Carl W. Fatzinger[2]

Genetically superior seed for reforestation of southern pines are produced in more than 10,000 acres of pine seed orchards in the southern United States. In the absence of pest management, insects and diseases can destroy more than 90 percent of the potential seed crops (Fatzinger et al. 1980). Several pesticides, however, have shown efficacy in reducing these losses to tolerable levels.

Insecticides were originally applied with hydraulic sprayers or mist blowers for the control of cone and seed insects. Liquid concentrations of the contact insecticide azinphos-methyl (Guthion 2L or 2S), when properly applied, were effective against these seed orchard insects. The systemic insecticide Carbofuran (10% granular) was registered in 1976 for use in southern pine seed orchards and is applied by incorporation into the soil with a John Deere Power-Till seeder. By the late 1970's, however, problems with both methods of pesticide application were detected. Effectiveness of Guthion applied with hydraulic sprayers or mist blowers for control of orchard insects decreased as the trees reached heights exceeding 45 feet. Granular applications of carbofuran proved to be ineffective against certain species of insects, especially coneworms (*Dioryctria* spp.).

A pilot study was conducted in 1980 to determine the feasibility of spraying southern pine seed orchards with fixed- and rotary-wing aircraft. These trials demonstrated adequate deposition of spray solutions in the crowns of sample trees (Barry et al. 1982). Helicopter applications resulted in only slightly better spray coverage on the crowns of trees than did applications by fixed-wing aircraft. Guidelines were developed for a second pilot study to evaluate aerial applications of pesticides for control of cone and seed insects in southern seed orchards.

The second pilot study, initiated in 1980, was in two loblolly pine seed orchards near Washington, N.C., and DeRidder, La. (Barber and Leonard 1985, Weatherby and Overgaard 1982). Aerial applications of Guthion and Pydrin were effective for the control of seed orchard insects (Figure 1). Cone survival from April 1980 through September 1981 was 13.7 percent in the untreated block, as compared to 85.6 and 81.8 percent in areas treated with Pydrin and Guthion, respectively. The main cause of cone or conelet damage during this study was the webbing coneworm, *Dioryctria disclusa* Heinrich. This coneworm destroyed nearly all of the loblolly pine cones in other orchards on the eastern seaboard during April 1980.

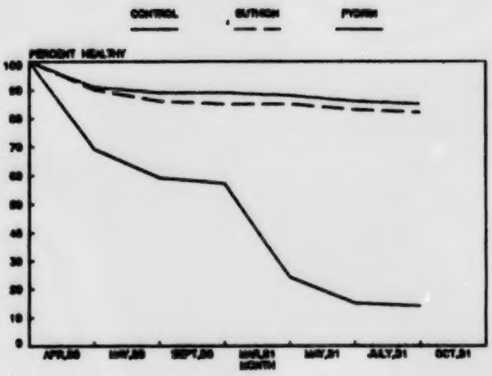

FIGURE 1: AERIAL PILOT PROJECT CONE SURVIVAL WASHINGTON, NC 4/80-9/81

The correct timing for effective insecticidal control of the webbing coneworm was determined during the second pilot study. The improved spray schedule proved to be effective for control of this insect during subsequent years. The efficacy of control also was enhanced by aerial application, because the insecticide could be applied to entire orchards in the short period of time available for adequate control.

The first recommendations for aerial applications of pesticides in southern seed orchards were made in 1981. Recommended parameters for helicopter operation are shown in Table 1. Except for speed, recommended parameters are the same for rotary- and fixed-wing aircraft. Various factors associated with aerial and ground application methods are compared in Table 2. The new technology developed was readily accepted by seed orchard personnel, who quickly changed from ground to aerial application of pesticides (Table 3).

The type of aircraft used in southern orchards is typically mandated by local availability of equipment. In some areas, aircraft are scarce, and orchard managers have little opportunity to negotiate the type of aircraft used, the exact timing of application, or calibration of the aircraft. In other agricultural areas, a larger choice of contract aircraft is available, and competitive bidding is the rule.

During a 1986 survey of several spray operations, we found that spray droplets often were too large and effective swath widths were far narrower than planned (Table 4).

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TABLE 1: Recommended helicopter application parameters

Parameter	1980	1981	1987
Swath width (ft.)	30	60	45-60
Speed (mph)	25	50	40-50
Application rate (GPA)	10	10	5-10^1
Physical spray characteristics	*2/*	*3/*	*4/*
Release height (ft.)	5	5	10-15
Droplet size VMD	350 μm	340 μm	350 μm
Droplet density Drops per cm^2	—	—	25

1/ Guthion or Pydrin applied at 10 GPA.
2/ Two passes over trees to yield 10 GPA.
3/ Two passes over tree rows to yield 10 GPA.
4/ One or two passes over trees to yield 5-10 GPA.

TABLE 2: Comparison of aerial to ground application methods in seed orchard

Factor	Aircraft	Liquid Ground Sprayers	Ground Soil Application
Access to orchard under muddy conditions	Yes	Poor	Poor
Soil compaction	No	Yes	Yes
Treat during favorable conditions	Yes	*1/*	*2/*
Time to treat orchard	Short	Long	Long *3/*
Pesticide drift	Less	More	Less
Manpower needs	Few	Many	Few
Spray volume	Low	High	N/A
Active ingredient per acre	Less	High	High *4/*
Personnel exposure from equipment operation	Less	More	Less

1/ Favorable weather conditions which favor depositing spray in the tree crowns and minimizing spray drift. Ground sprayers often are required to operate during unfavorable meteorological conditions to complete treatment within specified time.
2/ Soil must be dry enough to allow incorporation.
3/ Orchard treated in advance of insect outbreak.
4/ Normally requires only one application per year.

TABLE 3: Operational insecticide application methods used in southern pine seed orchards

	1978	1982	1987 Est.
Application Method	Percent of Orchards		
Air only	—	44	80
Air + granular	—	9	2
Ground spray only	15	18	16
Ground spray + granular incorporation	10	15	2
Granular incorporation only	75	15	—

Currently, we are developing a new technique for rapidly estimating pesticide residues in the field. A manganese tracer is added to the pesticide spray solution. Plastic spheres (1.75 inch diam.) are hung in the crowns of seed orchard trees as pesticide samplers (collectors) prior to applying the pesticide/manganese mixture. The quantities of manganese deposited on the spheres and on foliage samples is rapidly determined using a spectrophotometer. The manganese deposits are used to estimate the amounts of pesticide residues present on the spheres and foliage. We are currently investigating the degree of correlation between the manganese deposits and pesticide residues present on sprayed samples.

TABLE 4: 1986 spray application parameter results

	Orchard State Location					
Parameter	FL	AL	FL	GA	SC	VA
Gal/AC	10	10	10	10	5	10
Release ht. above trees (ft.)	20	15	30	10	10	—
Air speed (MPH)	100	100	100	40	60	50
Aircraft type	FW *1/*	FW	FW	RW *2/*	RW	RW
Swath planned	60	30	60	60	60	60
Swath actual *3/*	64	50	54	20-30	20	16
Droplet size VMD UM	385	700	526	600	385	1446

1/ Fixed-wing.
2/ Rotary-wing.
3/ The effective spray swath in feet equals that portion of the swath with drop density above 25 drops per cm^2. In the SC and GA tests, weather conditions were unfavorable; i.e., too windy.

The technique will allow orchard managers to rapidly analyze some of the problems currently encountered in seed orchards. Their questions include:

1. What is the optimum number of passes required over an orchard to deliver the desired spray deposition on foliage and strobili?
2. Should adjuvants be added to the pesticide solution?
3. What is the optimum droplet size?
4. How effective is a ULV application where the droplet size is reduced to around 125 microns, and what are the associated hazards of pesticide drift?
5. What are the seasonal effects on spray deposition, and how can we maximize deposition during all seasons?

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AN INTEGRATED APPROACH TO MANAGING THE DOUGLAS-FIR TUSSOCK MOTH OUTBREAK IN NORTHERN IDAHO IN 1986

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ABSTRACT — The DFTM research and development program completed in 1978 has provided information helpful in monitoring Douglas-fir tussock moth populations, predicting and evaluating outbreaks, suppressing populations when necessary, assessing host susceptibility, and reducing stand hazard. In 1986, anticipating an increasing tussock moth population in northern Idaho, land managers and pest management personnel initiated a preventive/suppressive program of virus application and silvicultural manipulations. Though population decline during this outbreak began independent of management efforts, and questions regarding the dynamics of tussock moth population remain, recently developed techniques better prepared us to forestall impacts of the pest.

RÉSUMÉ — Le programme de recherche et de développement sur la chenille à houppes du Douglas, terminé en 1978, a fourni des renseignements utiles en ce qui concerne la surveillance des populations de cet insecte, la prévision et l'évaluation des invasions, la suppression des populations lorsque nécessaire, l'évaluation de la sensibilité des hôtes et la réduction des dangers menaçant les peuplements. En 1986, en prévision d'un accroissement de la population de chenilles à houppes dans le nord de l'Idaho, les gestionnaires des terres et le personnel chargé de la lutte contre les nuisibles ont entrepris un programme de prévention/suppression comportant un traitement viral et des manipulations sylvicoles. Dans le cas de cette invasion, la population a commencé à baisser indépendamment des efforts de lutte et il reste à résoudre des questions relatives à la dynamique des populations de chenilles à houppes, mais des techniques récemment mises au point nous ont mieux préparés à contrer les effets de ce nuisible.

DFTM Research and Development Program

In 1973, DFTM was identified, along with gypsy moth and southern pine beetle, as one of the most significant forest insect pests in the nation. Special funding was allocated, and in 1975 intensive 3-year programs aimed at learning more about these pests and their impacts were begun. By 1978, at the culmination of the DFTM program, we had greatly expanded our knowledge of tussock moth biology, its interactions with its hosts, factors affecting population buildup and collapse, and ways to reduce associated impacts.

Because of the cyclic nature of tussock moth outbreaks, not since the termination of the DFTM research and development program in 1978 have we had an opportunity to fully apply the technology developed. The previous tussock moth outbreak had begun in the northwest in 1972 and collapsed in 1974. Recognizing an approximate 9-year interval between outbreaks, we anticipated the next population buildup would take place about 1983 or 1984. Population monitoring indicated that such an increase was likely. Armed with our newly developed technology, we were ready for it.

DFTM Biology and Damage Potential

The tussock moth is related to the gypsy moth, and outbreaks when they occur, can be nearly as spectacular. Mortality estimates for impacted stands approached 30 percent. Growth loss on trees not killed outright was also severe. The most recent major outbreak, in 1972-1974, covered hundreds of thousands of acres of host type throughout western United States and Canada.

The female tussock moth is flightless and so populations are not as "mobile" as some defoliator species in which both sexes are capable of flight. Populations tend to build in place, and lateral movement is not great. The male moth, a strong flier, is lured to the female's location with a powerful attractant pheromone. Once mated, the female deposits her egg masses on the cocoon from which she emerged. Overwintering is accomplished in the egg stage. There is one generation each year.

Technology Developed to Monitor, Evaluate, and Reduce DFTM Populations

1. Population Monitoring — Identification and synthesis of the tussock moth pheromone enabled us to develop a system for monitoring adult male population levels. Using a system of pheromone-baited sticky traps, we yearly assess population status in areas where, historically, tussock moth outbreaks have occurred.
2. Virus Determination — Identification of the naturally occurring nucleopolyhedrosis virus as a regulatory agent in the tussock moth population has not only given a means of controlling outbreaks, but a method for determining the vigor of developing ones.
3. Population Sampling — Egg mass and larval sampling techniques have been developed to aid our assessment of developing outbreaks. Subsequent evaluations help determine when control efforts may be warranted.

4. Computer Models — Models to assess population levels and outbreak potential have been developed. Outbreak models linked to stand prognosis models can predict long-term damage. These, in combination with socioeconomic models such as the forest planning model FORPLAN, help us determine the most cost-effective approach for dealing with tussock moth outbreaks.

5. Outbreak Evaluation — Evaluation of outbreak potential and associated impacts enable us to incorporate strategies to reduce tussock moth populations at the most effective and efficient point in the outbreak cycle.

6. Suppression — Methods for direct control of tussock moth populations have been developed. Presently, four materials are registered — two chemical pesticides: carbaryl and acephate; and two biologicals: *B.t.* and NPV. Under a given set of conditions, any one of the four might be the material of choice.

7. Silvicultural Control — A hazard-rating system for identifying stand conditions most conducive to population buildups and subsequent damage has been developed. Stands on poorer sites, overstocked with a dominance of host species, are more likely to harbor tussock moth outbreaks and sustain more damage when they occur. Methods to reduce stand susceptibility through reduction of host component, stand age, and stocking; and promotion of seral species and overall stand vigor have shown promise of lessening outbreak impacts.

Outbreak and Supression Program in North Idaho, 1986

Adult male trapping showed significant population increases in 1984. As a result, spring egg mass and larval surveys were initiated in 1985. These techniques also confirmed rising populations. A small pilot project was conducted in 1985 to evaluate the logistics of NPV application. Fall trap catches in 1985 nearly quadrupled from the 1984 level. With that, we began the evaluation process to determine the need for a suppression (or "prevention") program in 1986.

Based on historical information and trap-catch data, a potentially affected area was identified in northern Idaho. That larger area encompassed more than 300,000 acres. In compliance with the NEPA process, an Environmental Assessment was completed. A combined approach of identifying high-hazard sites, the encouragement of hazard reduction through silvicultural manipulations, and NPV application to areas of highest hazard was selected. Stand hazard rating, landowner inputs, and spring egg mass surveys enables us to reduce potential treatment area to approximately 32,000 acres. This area was geographically divided into 10 treatment blocks. Three additional blocks were identified which would not be treated with virus to serve as controls.

For population sampling, ten 3-tree plots were established in each block. Individual trees were host species, 30-60 feet tall, open grown and as full crowned as possible. While establishing sample plots, egg masses observed were flagged for development monitoring. As the spring progressed, both egg mass and foliage development were closely monitored.

Egg hatch was first observed May 29. At that time larval development sampling commenced by lower crown beating. When larval development in any one block reached the threshold of 50 percent second instar, that block was released for treatment. The next day, "prespray" larval population estimates were conducted by mid-crown sampling in that block. The first block was released for treatment June 5.

Throughout the development sampling period we became increasingly concerned about the low numbers of larvae being observed. Though our approach throughout the planning process was the early initiation of a viral epizootic in a nearly preventive strategy, we began to question whether measurable populations were sufficiently high for even that. After several blocks had been prespray sampled, and the first block had been treated with virus, we concluded that larval populations did not warrant treatment of the other 9 blocks. At that point, the virus application phase of the project was cancelled.

In an effort to determine, if we could, factors responsible for lower than anticipated populations, we continued both pre- and "postspray" larval sampling. Postspray sampling was conducted when larval development had reached 50 percent fifth instar. That sampling began July 7. Larvae collected during pre- and postspray sampling were kept and reared in the laboratory on artificial diet. Dates and causes of death were recorded. Results indicated that mortality attributable to naturally occurring virus totaled about 3 percent. Larval parasitism accounted for another 11 percent mortality. In total, more than 71 percent of the larvae completed their development and emerged as adults.

Subsequent pheromone trapping throughout the treatment area confirmed declining populations. Trap catches averaged approximately one-half of those trapped in 1985. Egg mass surveys in October further substantiated low and declining populations.

CONCLUSIONS

To date we have not proven what factors contributed to lower than anticipated tussock moth populations in 1986. We will continue to monitor the population in 1987, but are confident it is declining. Questions raised during 1986 remain:

- Is the established "alarm" threshold of 25 male moths per trap the appropriate level for all portions of the tussock moth range?
- What combinations of factors contribute to low population levels during some outbreak cycles?
- Some defoliation was observed in areas not identified as high hazard in 1986. Does the system we use to identify potential outbreak areas need to be refined or expanded?
- Is virus application an appropriate strategy for low tussock moth populations?

In conclusion, the DFTM research and development program enables us to predict and evaluate outbreak potential. It also helped us prepare for treatment possibilities. Still, questions regarding tussock moth population dynamics and interactions with their hosts remain. As we answer these questions, we will be even better prepared for the next outbreak.

OPERATIONAL USE OF NEW TECHNOLOGIES
1987 SPRUCE BUDWORM SUPPRESSION PROJECT

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ABSTRACT — In the past several years, there have been a number of changes in the area of aerial insecticide application. There are several new technologies that are becoming available that can improve the efficiency and accuracy of application. This paper discusses the use of digital flow meters, Pathlink recorders, the Forest Service Cramer Barry Grimm (FSCBG) computer model, and rotary nozzels on the western spruce budworm suppression projects in Washington and Oregon. It identifies problems encountered and the potential uses in the future.

RÉSUMÉ — Au cours de plusieurs années, de nombreuses modifications ont été apportées aux techniques d'épandage d'insecticides par voie aérienne. Plusieurs nouvelles technologies permettant d'améliorer l'efficacité et la précision des épandages sont en voie de diffusion. Cet article traite de l'utilisation de débitmètres numériques, d'enregistreuses Pathlink, du modèle informatique Forest Service Cramer Barry Grimm (FSCBG) et de buses rotatives pour le programme de suppression de la tordeuse des bourgeons de l'épinette de l'ouest dans l'État de Washington et l'Oregon. Les problèmes encourus sont mentionnés ainsi que les utilisations potentielles.

INTRODUCTION

Operational control projects for western spruce budworm in the Northwestern United States were first conducted in 1948. Between 1948 and 1962, over 4.7 million acres were treated with DDT at the rate of one pound per acre in one gallon of fuel oil. In 1972, DDT was banned from use in the United States, and other less persistant chemical insecticides such as malathion, carbaryl, mexacarbate, and acephate were registered for use. More recently, various formulations of the biological insecticide, *Bacillus thuringiensis* (B.t.), have been developed and improved, so that they are competitive, both in price and effectiveness, with the available chemical insecticides. The biological insecticides appear to be more acceptable to an environmentally aware public.

However, the currently registered chemical insecticides and B.t. are less persistent than DDT; and in many cases the mode of action is almost entirely dependant on ingestion by the target insect, resulting in a much narrower application window. Thus, the timing and delivery of the pesticide becomes extremely critical. Improvements have been made in the types of airplanes and helicopters used for application. But, only recently have advances been made to provide for some of the other areas of application technology.

During the 1987 western spruce budworm suppression projects in Washington and Oregon, an attempt was made to incorporate some of these newer technologies such as the Pathlink recorders and the FSCGB computer model for the first time. Other technology, such as the rotary atomizer nozzles had been used on previous projects. This paper discusses the extent of the use of the digital flow meter, rotary atomizer nozzles, the Pathlink recorders, and FSCGB computer model on these projects, the problems that were encountered, and the potential uses to further improve the area of pesticide application.

The 1987 Western Spruce Budworm Suppression Projects in the Pacific Northwest included three treatment areas or units. The Rimrock unit was located in Washington state near Yakima, and the other two units were located north and south of John Day in eastern Oregon. One application of 12 B.I.U.'s per acre with sufficient water added to make 96 ounces was applied to each area. The insecticides used were Thuricide 48 LV and Dipel 6L.

The Rimrock Unit treated 44,000 acres within the Rimrock Lake basin located on the east side of the Washington Cascades. The elevation ranges from 2400 feet to 6400 feet with a temperature range of 30 to 96 degrees F, and a humidity range of 30 to 100 percent. The application on this unit was made with Hiller Soloy and Lama 315B helicopters having a capacity of 70 to 150 gallons. Application was started on June 1, 1987 and completed on June 12, 1987.

The north and south John Day units were twenty to forty miles from John Day, Oregon, respectively, on the Malheur National Forest. The north unit treated 49,000, and the south unit treated 45,000 starting June 10, 1987 and completed treatment on June 23, 1987. The elevations ranged from 3000 to 6500 feet with a temperature range of 31 to 104 degrees F, and humidities of 25 to 100 percent. The application on the north unit was made with two Bell 205A1 Helicopter, one Turbo Thrush and one Turbo Agcat while the south unit application was made by two Bell 205A1 helicopters and one Turbo Thrush. All aircraft were turbine powered and there was an observation helicopter for each spray aircraft.

This contract was developed as a full service contract whereby the contractor furnished everything except the inspection and entomological information. The work was organized to facilitate a quality job with high production. Objectives were identified as; treating only budworm host type, even application of insecticide over treatment area in acceptable environmental conditions, during highest larval susceptibility, with safe manner and attitude. Key parts in the specifications were insecticide flow, atomization, organization, coverage and verification. To accomplish these, items such as Crop Hawk flow meters, Pathlink tracking, rotary atomizers and computer models were employed and evaluated.

FLOW METERS

Crop Hawk flow meters were first used on four Hiller Soloys in the 1985 western Spruce Budworm B.t. Pilot project, and found to be quite helpful especially when loads were divided between two units. Some operators claimed them to be inaccurate and undependable. These claims were based primarily on the fact that applicators were inexperienced at the installation and use of this device and often lacked the calibration factor for the material they were using. Once applicator and contract administrators better understood the benefits, they have been more accepted.

In the 1987 Project all aircraft were required to have flow meters of an adequate size so as not to create higher pressures. The benefits found were: 1) 25% less time needed for calibration; 2) the flow rate remained within 5% of the calibrated rates; 3) greater flexibility during the application of each load, and 4) rapid return to calibrated flow rates when found outside the 5% resulting in a significant time savings.

ROTARY ATOMIZERS

Rotary atomizers have been used on and off for the last twelve years in the Pacific Northwest in budworm projects. Since deposit and droplet size have become more critical with more specific application windows, narrower size droplet spectrums have been needed to produce satisfactory results. The wind tunnel at University California Davis (UC Davis) has been employed to evaluate B.t. materials sprayed with a variety of rotary atomizer nozzles. Since the B.t. plot evaluation in 1984, rotary nozzles have been used with less down time due to malfunctions and leaks with higher levels of deposit. The 1987 project was no exception. Characterization showed a narrower droplet spectrum with consistantly better deposit and greatly reduced characterization time. In the 1983 western spruce budworm suppression project flat fan and hollow cone nozzles were used. Average characterization time on this project was 3 days; and there was a great deal of difficulty in maintaining the character of the spray. In 1987, when all rotary atomizers were used, the characterization time was 1.2 days, and in only a few instances, were the drop sizes too large. This was usually caused by bad electrical brushes or bearings.

COMPUTERS/ANALYZERS

The use of computers are a recent development in our pesticide application work. In 1985 sketchy application of computers was made, primarily for the use of data and records. A few years of experience has allowed for more professional development of data based programs which has improved our confidence in the output. Computers are now an essential part of the record keeping and report process of a large spray contract. In this project three computers were used. The main Forest System Data General was used for mail and external communications while two Compaq personal computers were used for project data, analysis of Pathlink recordings and, FSCBG model simulations and spray assessment programs.

PLANNING AND OPERATIONS

In this project, the first uses were in the host type mapping, where a CALCOMP 9000 digitized plotting board was joined with a HP9000 computer. Point locations from the area perimeter from original maps were plotted and stored in a data base. The treatment area can be computed from the stored data and the map scale of any area can be changed with the output plotted on a HP7580B plotter which is then traced onto a map of the appropriate size.

The status of insect development by entomological block was entered, as soon as available, with release dates which were updated daily and incorporated into the next days operation plan. The initial entries also identified, by letter and number, each entomological block detailed with a gross area and an estimated net area in acres. Also included were identified hazards to aircraft by treatment block. Each day updates included all spraying by block and aircraft with entomological update. From this base, a report gave spray acres completed, acres not completed, hazards to aircraft, and new areas available. The next day's operation plan was then developed from this information. This work was done with 90% fewer errors and 25% fewer personnel resulting in a real savings to the project.

APPLICATION AND MONITORING

Pathlink is a relatively new development as a tracking device in aerial application, manufactured by Pathcore. It was used on a limited basis in the 1986 Oregon Gypsy Moth Project which showed it to be a feasible device for documenting and displaying flight path and application area. It also has other benefits, such as monitoring the timing of flow rates, distance of flight and distance of flight while making application. However, the basic benefit is having a hard record of the area treated and relative distances between flight lines. The two Compaq Computers serve as the analyzers for the Pathlink Recorders. They were modified by Pathcor to serve in this role. The project purchased three recorders and borrowed seven additional units from the USDA Animal and Plant Health Inspection Service (APHIS).

The Pathlink System is a combination of computer hardware and software, and a Loran C longitude, latitude positioning device. The recording hardware consists of the Loran receiver to identify position location, a small micro computer that records data from inputs to a bubble cassette, a rechargeable battery, and input points for other data such as when the aircraft is spraying, altitude, temperature, airspeed, and so on. The recording hardware is all contained in an aluminum case which has shown itself to be very durable. The analyzing portion of the system consists of a personal computer, bubble cassette reader, printer, and program software.

There were some problems with the use of the units. In the Turbo Thrush and Turbo Agcat there was no space in the cockpit for the unit. On the Rimrock Unit, which had all Hiller 12E Soloys and one Lama 315B, the problem was antenna and antenna ground plane, which resulted in erratic information. It was first thought that the close distance to the George Washington transmitter was at fault, but use elsewhere showed the problem to be antenna ground plane related. The Lama 315B also has an antenna ground plane problem due to the large amount of plexiglass it has in the cabin area. One Bell 205 A1 had excellent results where the Pathlink recorder was working 95% of the time. The other remaining 5% involved incorrect operation of the equipment. The other three Bell 205 A1's had varying results with problems related to poor location of the antenna on the right side above the cargo door. This resulted in a loss of receiver signal when the aircraft did an abrupt right turn.

When the recorders could not be mounted in the application aircraft, it was mounted in the observation helicopter which was following the spray ship. The main problem associated with the observation aircraft, was that these ships often had the antenna improperly mounted. The antenna were usually mounted on the bottom of the aircraft, resulting in a recorded reversed position location. A Pathlink representative inspected all aircraft and found many deficiencies in installation, usually related to antenna and or ground plane.

The benefiting uses on this project were in monitoring flow rates, consistancy of coverage and area covered, some block boundary determination, and pilot performance and production rates. We believe that one of the greatest benefits is its use to locate perimeter and interior boundaries accurately in a short amount of time. However, to make a system such as this work, knowledgable personnel must be available to install and troubleshoot the recording equipment. A copy of the output of one aircraft for one day is shown in Figures 1 and 2.

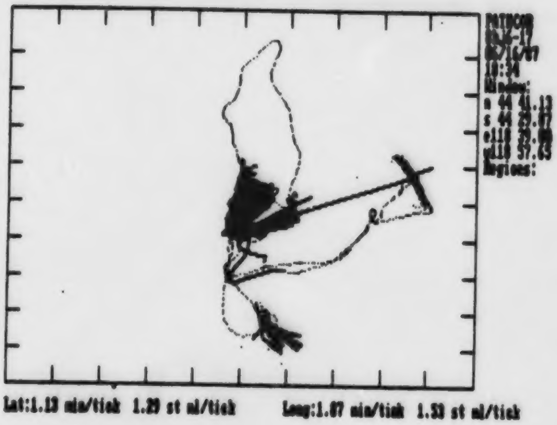
18:34
Regions:
Lat:1.13 min/tick 1.29 st mi/tick
Long:1.07 min/tick 1.53 st mi/tick

FIGURE 1: PATHLINK VISUAL DISPLAY

Application flight for Bell 205A1 N58HJ on June 17, 1987 on the North John Day unit.

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                          PATHLINK ANALYZER SUMMARY

Flight name: 8hj6-17
Date of flight: 06/16/87, 18:34

Total distance flown: 201.37 mi
Total time flown:   1 hr(s) 34 min(s) 54 sec(s)
Total distance treated: 82.58 mi
Total distance not treated: 118.79 mi
Total time treated: 40 min(s) 12 sec(s)
Total time not treated: 54 min(s) 42 sec(s)
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FIGURE 2: PATHLINK ANALYZER SUMMARY

Data report for application flight of N58HJ as shown in Figure 1.

SPRAY DEPOSIT AND ASSESSMENT

As is in many aerial application projects there are always differences in what we think we see, what we want to see and what is really happening to the spray deposit. For this reason we started to compare the FSCBG model predictions with the environmental conditions we were applying. The FSCBG computer model is a model that was developed by the U.S.D.A. Forest Service and the U.S. Army with some assistance from the National Aeronautics and Space Administration (NASA) to predict what happens to the spray drops once they leave the nozzle.

B.t. has a relatively narrow application window and is easily affected by adverse application conditions. Sometimes the "go" or "no go" decision is pushed in favor of production in the face of marginal conditions, without full realization of the consequences. By use of the model it was hoped that personnel would better understand what was happening to the spray material out of reach of their weather instruments.

We also wanted to evaluate the model under field conditions as to the accuracy of predictions of deposit on assessment cards in different canopy types. From the information available there appears to be very definite similarities between model and field results. Trends for droplet size and numbers usually were within 25 percent in the limited number of samples used. The two problems encountered were in the sampling devices and defining the canopy. The model indicates a larger number of small droplets than were detected on the Kromcote sample cards. These cards were suspended about eighteen inches from the ground and would not detect horizontally air borne droplets. The canopy descriptions were limited; and there would be significant value in preparing stand type descriptions and categorizing them, to apply as coded in the field, to the model.

The model was available only for limited times due to making improvements in the program and lack of personnel. There needs to be more studies of the correlation between field conditions and the model predictions using a standardized assessment system and developed canopy types. I have found the FSCBG Model valuable in developing application strategy in equipment specifications and application guidelines. These applications appear to be valid.

SUMMARY

In summary, this technical equipment requires personnel with more experience and greater knowledge of the equipment. Initially, it will require more time to realize the total benefits, but as resistance to the use of this equipment is reduced, available application time can be increased, along with better application, monitoring, record and data processing, and overall project efficiency.

IMPROVEMENTS IN SPRAY TECHNOLOGY USED TO CONTROL DOTHISTROMA NEEDLE-BLIGHT IN NEW ZEALAND PINE PLANTATIONS

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ABSTRACT — A disease of *Pinus radiata* caused by the fungus *Dothistroma pini* may be controlled using 4.16 kg/ha of copper oxychloride, applied in 20 litres of water per hectare, using fixed-wing aircraft fitted with boom and nozzle equipment.

Trials have shown that effective disease control can be achieved using a total spray volume of 5 litres/ha containing 1.66 kg copper oxychloride plus 2 litres of an emulsifiable oil, mixed in water, and applied using Micronair rotary atomisers.

The average cost of disease control has been reduced by 33% since the introduction of the 5 litres/ha application technique.

RÉSUMÉ — L'épandage, au moyen d'un avion à ailes fixes muni d'une rampe de pulvérisation avec buses, d'une solution d'oxychlorure de cuivre à raison de 4,16 kg/ha dans 20 litres d'eau permet de lutter contre une maladie de *Pinus radiata* causée par le champignon *Dothistroma pini*.

Des essais ont montré que la maladie peut être limitée efficacement par l'épandage, au moyen d'un atomiseur rotatif Micronair, d'un volume total de 5 L/ha d'une solution renfermant 1,66 kg d'oxychlorure de cuivre et 2 litres d'une huile émulsionnable mélangée à l'eau.

Depuis l'introduction de cette nouvelle technique, le coût moyen de la luttre contre cette maladie a baissé de 33 %.

INTRODUCTION

New Zealand has made a large investment in exotic pines, the main species being *Pinus radiata* D. Don. Almost 1 million ha have now been planted throughout the country.

A needle blight caused by the fungus *Dothistroma pini* Hulbary was positively identified on *P. radiata* in 1964 (Gilmour 1967). By 1966 the disease was present in 40 000 ha of pine plantation, of which 11 000 hectares were severely affected (Gilmour *et al.* 1973). Although the disease rarely kills pines, it does reduce growth (Whyte 1976; van der Pas 1981).

Following the discovery in Kenya that the disease could be controlled by applications of copper fungicides (Gibson *et al.* 1966), trial aerial applications of several copper fungicides were made in New Zealand, in 1965, to heavily diseased stands of *P. radiata* (Gilmour and Noorderhaven 1973). All of the fungicides tested were equally effective in controlling the disease when applied at rates of 4.5 kg/ha, using a 50% wettable powder suspended in 56 litres of water per hectare. The trials also showed the importance of the correct timing of the fungicidal application (Gilmour and Noorderhaven 1971).

An aerial spray programme to control the disease was initiated in December 1966 using fixed-wing aircraft fitted with either conventional boom and nozzle equipment or Micronair rotary atomisers (Gilmour *et al.* 1973).

Apart from the replacement of Micronair atomisers with conventional nozzles from 1968 on, the operation remained unchanged until 1980. In 1981 the application volume was reduced to 20 litres/ha and the nozzle type and orientation were specified to ensure the production of a spray with a volume median diameter (v.m.d.) of 200 microns (Kershaw *et al.* 1982).

The data of Himmel and Moore (1969) and Barry and Ekblad (1978) suggest that more spray would be intercepted by pine needles if applied in droplets with a diameter of 70 microns or less. The trials reported here were undertaken to investigate the possibility of improving the efficiency of disease-control operations by using rotary atomisers to produce droplets in this size range.

MATERIALS AND METHODS

Aerial spray trials were undertaken under operational conditions in two successive summers, in order to compare the effectiveness of two different spray application systems which were used to apply copper fungicides to *P. radiata* trees for the control of *D. pini*.

Trial Locations

Trials were established in *P. radiata* plantations at two locations: one in Kaingaroa Forest on a flat site, and the other on the Mamaku Plateau in broken country. In Kaingaroa Forest the trees were between 3 and 4 years old; on the Mamaku Plateau the trees were between 4 and 7 years old. Both locations are in the central North Island of New Zealand, where pine plantations develop high levels of disease in the years in which the weather conditions are suitable for disease development.

Treatments

The effectiveness of the standard treatment, an aqueous spray containing 4.16 kg of copper oxychloride in a total volume of 20 litres/ha, was compared with that of an oil-in-water emulsion containing different rates of copper fungicides, applied at 5 litres/ha. The rates of fungicide and oils are listed in Table 1. The months in which the spraying was carried out are given in Table 2.

TABLE 1: Fungicide treatments

Mixture	Fungicide	Fungicide rate (kg/ha)	Additives	Additive volume (litres/ha)	Application volume (litres/ha)	Atomiser
1	COC	4.16	–	–	20	D6-45
2	COC	1.40	Oil*	2	5	AU 5000
3	Cu_2O	0.79	Amelosan†	1	5	AU 5000
4	COC	1.66	Oil‡	2	5	AU 5000

COC Copper oxychloride 50% WP
Cu_2O Cuprous oxide 89% Sn in oil (Oleocuivre supplied by Hoechst New Zealand Limited)
* Premium Late Winter Oil (Shell Chemicals New Zealand Ltd)
† Anti-evaporant Spray Adjuvant (Hoechst New Zealand Ltd)
‡ Crop Oil (BP New Zealand Ltd)

Application Equipment

Fixed-wing aircraft were used to apply the fungicide mixtures: i.e., either a Fletcher FU 400 or a Cessna Agwagon for the 20 litres/ha application, and a Fletcher FU 400 for all of the 5 litres/ha applications.

For the 20 litres/ha application, new D6-45 (Spraying Systems Ltd) disc and core nozzles were fitted prior to the commencement of each trial. The boom was rotated so that the nozzles pointed 45° forward and down, and the boom length was restricted to approximately 75% of the wing span. For the 5 litres/ha applications, four Micronair AU 5000 rotary atomisers, fitted with CPB 250 fan blades set fully fine, were clamped onto the spray boom. The outer units were positioned so that the spray did not become entrained in the wing-tip vortices. A Micronair flow meter was fitted giving a readout of the flow-rate to the pilot.

Spray Application

The spray systems were checked for leaks and adjusted to give the correct spray output before spraying.

Each spray formulation was mixed prior to being loaded into the aircraft, and maintained in suspension during the ferry flight by bypass agitation.

The pilot was requested to spray at a bout width of 20 m, and to maintain a height of between 4 and 6 m above the tops of the trees. The Agwagon aircraft flew at a speed of 95 knots and the Fletcher aircraft flew at 105 knots during spraying.

Flagmen were used to provide flightline guidance in the Kaingaroa trial. The terrain dictated that no such assistance could be given to the pilot in the Mamaku trials — a situation which exists in operational spraying.

Spray Droplet Size Assessment

Samples of spray droplets were collected either on cast-coated card or on magnesium-oxide-coated slides positioned approximately 1 m above the ground on roadways or in clearings. Five hundred droplets from each spray pattern were measured using a microscope fitted with an eyepiece graticule. The size of the original droplet spectrum was calculated after making an allowance for the spread of the spray droplets on the card or slides. The spread factor of each formulation was determined in the laboratory, by measuring the size of the stains produced on the card by a stream of mono-sized drops of a known size.

Meteorological Conditions

The meteorological conditions were monitored continuously during spraying. Spraying was stopped if the wind speed exceeded 16 km/h, the temperature rose above 20°C, or the humidity dropped below 50%.

Disease Assessments

All blocks were assessed for average disease-levels, following the procedures described by Kershaw *et al.* (1982) where the percentage of unsuppressed green tree crown which is diseased is assessed. Assessments were made in the September prior to spraying and again in the following September.

In the Kaingaroa trial, disease levels were assessed independently, by two experienced observers, on 200 individual trees per block. In the Mamaku trials, the topography and the density of the undergrowth necessitated the use of the aerial-survey method of disease assessment. The average disease-level in each treatment block (neglecting the margins) was assessed independently, by two experienced assessors, from a helicopter.

RESULTS AND DISCUSSION

Disease levels before and after spraying in the various trials are given in Table 2. In the Kaingaroa trial there was no significant difference ($p = 0.05$) between the disease levels found in either of the sprayed blocks, but both had significantly lower disease levels than those found in the unsprayed control. Under the conditions experienced in the trial, the use of Micronair spray equipment with a reduced fungicide rate and application volume did not decrease the effectiveness of the spray application.

In the 1981/82 Mamaku trial, spraying at either the 20 litres/ha rate or the 5 litres/ha rate produced similar reductions in the disease level. As cuprous oxide contains 89% copper by weight, the fungicide application rate in the 5 litres/ha treatment, in terms of copper metal equivalent per hectare, is the same as that used in the 5 litres/ha treatment in the Kaingaroa trial.

A comparable reduction in disease levels was achieved in the 1982/83 Mamaku trial, when either 4.16 kg of copper oxychloride was applied in 20 litres of water per hectare or when 1.66 kg of copper oxychloride was applied in a mixture of water and emulsifiable oil at 5 litres per hectare. In this trial the disease level in the unsprayed control also fell, in contrast to the increase in the previous year. The development of the disease is favoured by long periods of leaf wetness (Gadgil 1977). The decrease in disease intensity in the unsprayed treatment suggests that the climate was less suitable for disease development than in the previous year. This was reflected in a countrywide reduction in disease levels in September 1983 caused by a lower rainfall.

TABLE 2: Trial summary

Block	Area (ha)	Application volume (litres/ha)	Fungicide treatment*	Month sprayed†	Droplet v.m.d.‡ (nm)	Disease levels (%)§	
						Before spraying	After spraying
Kaingaroa (1981-82)							
263	77	20	1	N	188	25	28
307	101	5	2	N	— ‖	33	22
249	89	—	—	—	—	29	50
Mamaku (1981-82)							
A	20	20	1	N	134	75	55
B	124	20	1	N+F	134+225	75	40
C	61	5	3	N	45	65	35
D	62	5	3	N+F	45+45	60	25
E	72	—	—	—	—	60	80
Mamaku (1982-83)							
F	108	20	1	N	227	45	20
G	67	20	1	N+F	227+181	35	5
H	98	5	4	N	55	42	7
I	76	5	4	N+F	55+75	45	5
J	90	—	—	—	—	37	30

* Details given in Table 1
† N = November, F = February
‡ Volume median diameter
§ Percentage unsuppressed green crown which is diseased
‖ Not measured

Aerial assessments made by two observers are considered to have a coefficient of variation of about 25% (van der Pas *et al.* 1984). All of the 5 litres/ha applications show a greater reduction than this in disease levels when compared with the unsprayed plots, but do not differ from the trees sprayed at 20 litres/ha.

The success of the spray technique using Micronair equipment is probably attributable to two factors:

(1) oil has been shown to increase the effectiveness of copper fungicides in nursery spray trials (Gilmour and Vanner 1972), and was incorporated in the spray mixture to reduce evaporation

(2) the use of smaller droplets, which result in a higher proportion of the spray being caught by the foliage (Joyce and Beaumont 1978).

As a result of these trials, all operational spraying to control pine needle blight, since 1984, has been undertaken using 1.66 kg/ha of copper oxychloride in a spray volume of 5 litres/ha. The cost of spraying has been reduced by approximately one third and this has repaid the initial capital cost of re-equipping the aircraft, many times over, in the first year.

ACKNOWLEDGEMENTS

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FIELD VALIDATION OF A FOLIAR DEPOSIT BIOASSAY FOR *BACILLUS THURINGIENSIS*

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ABSTRACT — This paper describes the use of a novel feeding inhibition bioassay for the determination of *B.t.* deposits on foliage from four experimental spray blocks. The results of correlations between feeding inhibition, foliar deposit as determined by microscopic analysis (droplets per needle) and reduction in defoliation are presented and discussed for both individual tree and bulked bioassay samples.

RÉSUMÉ — Ce papier décrit l'utilisation d'une nouvelle nourriture interdiction d'un essai biologique "Feeding inhibition bioassay" pour la détermination de dépôt *B.t.* sur les feuillages venant de quatre billot vapousateur en essai. Le resultat de corrélation entre la nourriture interdiction, le dépôt de foliaire (goutlettes par aiguille) comme déterminer par l'analyse microscopique et la réduction en défeuillaison sont présenter et discuter pour les échantillons individuels et en groupe d'essai biologique.

INTRODUCTION

Recent work by Wiesner and Thomas (in preparation) has demonstrated a strong relationship between the inhibition of feeding by sixth instar spruce budworm larvae on artificial diet and the concentration of *Bacillus thuringiensis*. var. Kurstaki (*B.t.*) within the diet.

The diet, containing 85% powdered cellulose, is low in nutritional value; consequently, the larvae typically consume large quantities of the diet and, in turn, produce large quantities of frass (faeces). By incorporating various amounts of *B.t.* into the diet and determining the reduction in frass production relative to controls, it is possible to correlate percent feeding inhibition with *B.t.* concentration. The work also demonstrated that similar correlations exist when the *B.t.* is first sprayed onto conifer foliage, recovered by washing and the washes incorporated into the diet.

This bioassay can be completed within 24 hours and would therefore appear to have potential as a rapid method for determining *B.t.* deposits in spray blocks.

The work of Fast *et al.* (1984) established strong correlations between reduction in defoliation and spray deposit on conifer foliage measured by microscopic analysis. The objective of the present study was to determine whether similar correlations could be demonstrated between the feeding inhibition bioassay and foliar deposit and reduction in defoliation, respectively.

METHODS

Spray Block Sampling

Aerial applications of four undiluted *B.t.* formulations (Dipel 6AF, Dipel 8AF, Dipel 8NES and Dipel 12L) all at 30 BIU/ha. were made to four 200 ha. blocks of mixed spruce/fir forest. In each block, sixty sample trees were selected with each tree being sampled from the mid crown area for the following:

1. Prespray larval count
2. Post spray deposit-bioassay
3. Post spray deposit-microscopic analysis
4. Final defoliation and larval survival

Immediately post-spray duplicate sample branches (ca. 45 m) were collected from each tree. From one branch of each pair, eight randomly chosen twigs were cut and placed in labelled storage racks for subsequent microscopic analysis. The second branch was labelled and placed in a plastic bag for deposit bioassay. All samples were stored at −10°C prior to further analysis.

Deposit Analysis

(i) Microscopic Technique

Microscopic deposit analyses were carried out on ten randomly selected needles from each twig for a total of eighty needles per sample.

Deposits of the aqueous 6AF and 8AF formulations (to which had been added the non-insecticidal dye, Erio Acid Red XB400% at a rate of 0.2% by weight) were counted under visible light. The oil based 8NES and 12L formulations (which were supplied premixed with a particulate fluorescent orange dye) were examined in darkness under ultraviolet light.

(ii) Bioassay Techniques

Based upon results of microscopic deposit analyses, bioassays were conducted on selected samples as indicated below:

Dipel 6AF — 14 individual samples

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Dipel 8AF — 24 individual samples

Dipel 8NES — 3 bulk samples (each of five individual samples)

Dipel 12L — 3 bulk samples (each of five individual samples)

The bioassay procedure was as follows:

One hundred grams of each foliage sample were first soaked at room temperature for fifteen minutes in 750 ml of 0.01% Triton X-100 wash solution prior to being placed in a sonicating bath for a further fifteen minutes. After this time the wash solution was decanted, the foliage rinsed with 250 ml of fresh solution and the washes combined.

Freeze-dried diet powder was prepared by thoroughly mixing 100 g of freeze-dried ground and screened diet (McMorran, 1965) with 700 g of Alpha Cel.

3.3 g of diet powder was mixed with 10 ml of wash solution to form a thick paste. The paste was divided among twenty-four microvials, one of which was placed in each of twenty-four 10 × 35 mm disposable petri dishes. One sixth instar spruce budworm larvae (*ca.* 1 day-old) was placed in each dish. The larvae were then held at 26°C in a 17:7 light/dark cycle for eighteen hours. The larvae were then killed by placing the dishes in a freezer (−10°C). The larvae and the remaining diet were removed from the dishes and the frass was dried at 50°C for 1 hr. The dried frass produced by each larva was weighed.

The above procedure was also carried out with twenty-four control larvae on *B.t.* free diet.

Feeding inhibition caused by B.t. in the diet was then calculated as follows:

$$\% \text{ Feeding Inhibition} = \frac{C{-}T^{*}\ 100}{C}$$

Where: C = mean frass weight (controls)
T = mean frass weight (test)

RESULTS AND DISCUSSION

Feeding inhibition was correlated with deposit as determined by microscopic analysis and with reduction in defoliation as shown in Figures 1-3.

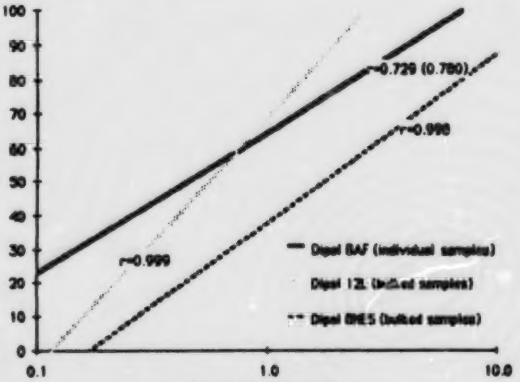


FIGURE 1: REGRESSION LINES AND CORRELATION CO-EFFICIENTS: MICROSCOPIC DEPOSIT ASSESSMENT vs. FEEDING INHIBITION BIO-ASSAY

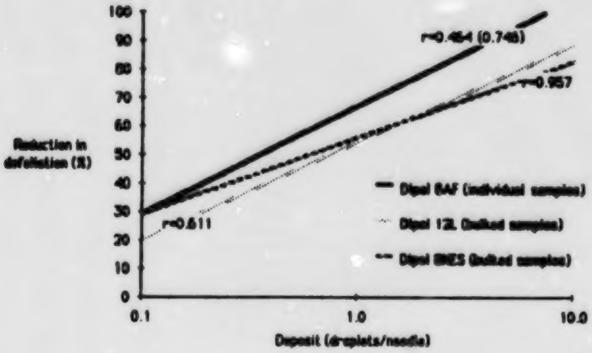
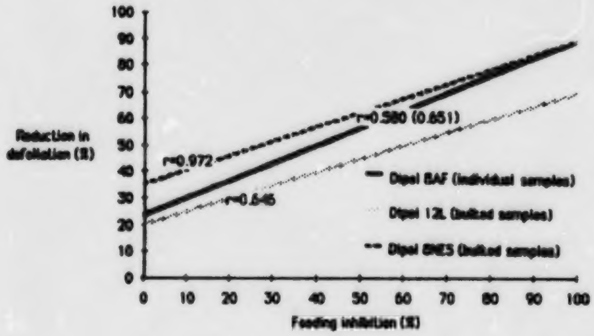


FIGURE 2: REGRESSION LINES AND CORRELATION CO-EFFICIENTS: MICROSCOPIC DEPOSIT ASSESSMENT vs. REDUCTION IN DEFOLIATION



* result with outlying data points removed shown in parentheses

FIGURE 3: REGRESSION LINES AND CORRELATION CO-EFFICIENTS: FEEDING INHIBITION BIO-ASSAY vs. REDUCTION IN DEFOLIATION

Spray deposit in the 6AF block was extremely low due to the adverse meteorological conditions. Consequently, no useful correlations could be derived. However, in the 8AF block very strong correlations were obtained between feeding inhibition and deposit (droplets per needle), while both droplets per needle and feeding inhibition correlated well with reduction in defoliation.

In the blocks which were bulk sampled (Dipel 8NES and Dipel 12L) even stronger correlations were obtained. As expected, the regression line for 12L lay above that for 8NES in the bioassay vs. deposit correlation. However, in the field evaluation of reduction in defoliation, no significant difference was seen between the 12L and the 8NES formulations. This could be due to:

(a) Poorer weather condition in the 12L block (e.g. post-spray rain shower);

(b) The 64 BIU/gal. (8NES) formulation being sufficiently potent that increasing potency to 96 BIU/gal. (12L) does not significantly improve efficacy.

While in the past we have documented improvement of efficacy with increasing potency, it is possible that at some potency level the effect will begin to level off. Whether this point of diminishing return has been passed by going from 64 to 96 BIU/gal. cannot be determined with this single experiment. Certainly, the operational benefits of reduced application volume still apply.

CONCLUSIONS

The results demonstrate that the feeding inhibition bioassay is at least as good as the microscopic (droplets per needle) method for determining *B.t.* deposits on foliage while offering the advantage of bulk sampling. It is, therefore, a useful method for the routine monitoring of operational and experimental *B.t.* spray deposits.

ACKNOWLEDGEMENTS

This study was funded by Abbott Laboratories Ltd.

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IMPROVED EQUIPMENT FOR ACCURATE AERIAL APPLICATION OF GRANULAR FERTILISERS TO FORESTS

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ABSTRACT — Fertilisers were first applied to pine plantations in New Zealand in the 1950s, but it was not until the 1970s that large-scale programmes were introduced in order to correct nutrient deficiencies and improve tree growth.

Early applications were made using fixed-wing aircraft, and evidence of poor distribution of fertiliser was seen in the uneven growth response of the trees. To compensate for this, more than twice the base rate of fertiliser had to be applied to ensure that all areas received sufficient amounts to promote good growth.

Major improvements comprised the introduction of helicopters with underslung hoppers fitted with spinner distributors to ensure a more even distribution of granules, and the production of fertilisers with a uniform granule size. Modifications to the spinner design have ensured that the granules are not shattered.

The lack of guiding features in many forests made it almost impossible for pilots to fly accurately-spaced bout widths. The introduction of an electronic guidance system, the Flying Flagman, has eliminated this problem.

Modifications to the Flying Flagman system have provided the pilot with a readout of ground speed, via an L.E.D. display. The ground speed information is also used to open and close the hopper gate through a proportional controller. Variations in ground speed no longer result in a change in application rate. In combination, these improvements have made it possible to more than halve the rate of fertiliser application.

The system is equally suitable for applying granular pesticides, and has been used operationally to apply granular herbicides for tree-releasing and poison baits for rabbit and opossum control.

RÉSUMÉ — En Nouvelle-Zélande, des engrais ont été épandus pour la première fois sur des plantations de pins dans les années 1950, mais ce n'est pas avant les années 1970 que des programmes de grande envergure ont été introduits afin de corriger les carences en éléments nutritifs et d'améliorer la croissance des arbres.

Au début, les épandages étaient effectués à l'aide d'avions, et la mauvaise répartition de l'engrais se manifestait par une croissance inégale des arbres. Pour compenser, il fallait appliquer l'engrais à un taux égal au double du taux de base afin de s'assurer que toutes les zones recevaient des quantités d'engrais suffisantes pour favoriser une bonne croissance.

Parmi les améliorations importantes, on compte l'introduction d'hélicoptères équipés de trémie suspendues munies d'épandeuses centrifuges, pour assurer une répartition encore plus uniforme des granules, et la production d'engrais de granulométrie uniforme. Des modifications apportées aux épandeuses préviennent la fragmentation des granules.

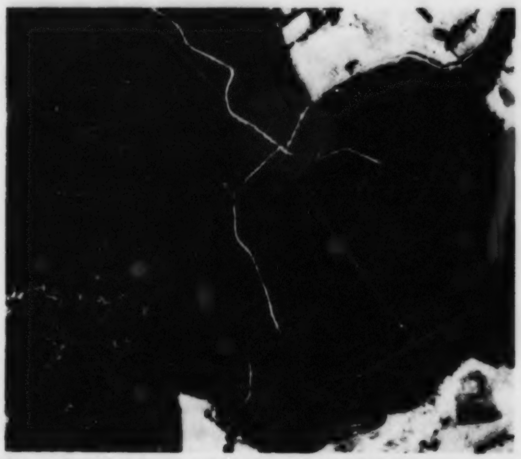
INTRODUCTION

Fertilisers were first applied to pine plantations in New Zealand in the 1950s, but it was not until the 1970s that large-scale programmes were introduced in order to correct nutrient defiencies and improve tree growth.

The use of fertilisers has now become a routine part of efficient forest management in a number of forests in New Zealand. Many forests are located on infertile soils that are unsuitable for agriculture. Although trees generally have lower nutrient demands than agricultural crops, some of these soils do not contain adequate nutrient levels for good forest growth. In particular, nitrogen, phosphorus, and boron deficiencies severely affect tree growth in parts of both the North and South Islands of New Zealand. Unless adequate fertilisation programmes are maintained, tree growth and timber quality can decline (Hunter and Graham 1982; Hunter 1984).

Phosphorus deficiency is the major nutrient deficiency limiting pasture growth on much of New Zealand's farmland, but because of steep topography it is often impracticable to spread fertiliser from the ground. In the 1940s, the aerial application of superphosphate was pioneered using modified "Tiger Moth" aircraft. It soon became evident that aerial topdressing was the answer to increasing productivity, and an extensive industry soon developed.

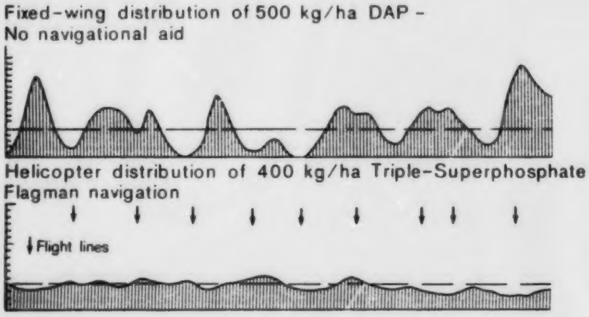
New aircraft with improved performance have been designed specifically for aerial topdressing. However, while factors such as carrying capacity, speed, and manoeuverability, have been improved, the fertiliser is still "released out of a hole in the bottom of the aeroplane". This is a major factor contributing to the uneven spread of fertiliser (Forest Research Institute 1982). Uneven distribution has not been regarded as a serious disadvantage in the pastoral situation where the frequency of repeat application and the fertility transfer by grazing animals are considered (by some) to be effective counter-acting factors. However, after the aerial applications of fertilisers to forests began in the 1950s, it soon became evident that, with fertiliser applications 4 to 10 years apart and no animal fertility transfer, uneven distribution was a major contributing factor in variability in tree size, thereby reducing the profitability of harvested trees (Fig. 1).



Part of Riverhead Forest aerially topdressed in 1959. The uneven growth response -the strip effect- evident in this photograph taken in 1969 has been largely caused by uneven fertiliser distribution. (FRI BW 51988)

FIGURE 1: UNEVEN GROWTH RESPONSE

It was not until the late 1970s that major steps were taken to improve fertiliser distribution over forests. A change was then made to using helicopters which are guided by an electronic navigation and tracking system, called a Flying Flagman, and equipped with a fertiliser hopper and a motor-driven spinner (Fig. 2). This combination aimed to improve fertiliser distribution across each swath and to ensure that flight lines were evenly spaced and parallel.



Fixed-wing distribution of 500 kg/ha DAP - No navigational aid

Helicopter distribution of 400 kg/ha Triple-Superphosphate Flagman navigation

FIGURE 2: COMPARISON OF FERTILISER DISTRIBUTION ACROSS A FOREST

Although significant improvements in overall fertiliser spread were noticed (Will and Hedderwick 1984), it was felt that further improvements in the navigation and tracking equipment and fertiliser hopper were both desirable and possible. The increasing use of high-analysis fertilisers and ever-increasing costs helped to prompt this concern.

RESEARCH NEEDS: KEY AREAS IDENTIFIED

In order to further improve the distribution of fertiliser, the following research and development needs were identified:

1. Fertiliser flow-rate of a given material, together with the helicopter velocity, would enable a "kilogram per hectare" rate for a plantation to be calculated. To keep this rate constant during sowing, it would be advantageous to have an accurate display of ground speed for the pilot. Air-speed indications at such low velocities are notoriously inaccurate, because of head and tail winds and the characteristics of the helicopter's velocity sensor (pitot tube).

2. The flow-rate from the hopper should automatically adjust itself in relation to the helicopter ground speed, in order to maintain the desired kilogram per hectare rate.

3. The hopper spinner should be hydraulically driven from a power take-off on the helicopter, increasing both the reliability and the power-to-weight ratio.

4. The spinner should be redesigned to give a more even swath by:

   (a) decreasing the shatter of fertiliser granules on its vanes

   (b) preventing granules from hitting the hopper leg structure.

5. The hopper capacity should be increased to accommodate 800 kg fertiliser bags, and made wide enough to allow "self loading" by the helicopter.

The Forest Research Institute responded to these requirements by developing and manufacturing a new hopper and spinner to improve the level of performance and to suit the high-analysis fertilisers used today.

The prototype has been used operationally during the 1986-87 topdressing season and can provide the pilot with all of the advantages of the Flying Flagman system, together with the following:

1. The hopper has a constant flow-rate through to the spinner and can hold 800 kg of urea, a nitrogenous fertiliser with a greater volume for a given weight than most other fertilisers used today (Fig. 3).

2. The spinner has down-turned and angled slingers which increase the swath width and virtually eliminate any shatter of granulated fertilisers (Fig. 4). The spinner is hydraulically driven, cheap to manufacture, and light.

3. The pilot has been provided with an indication of the helicopter ground speed during operation.

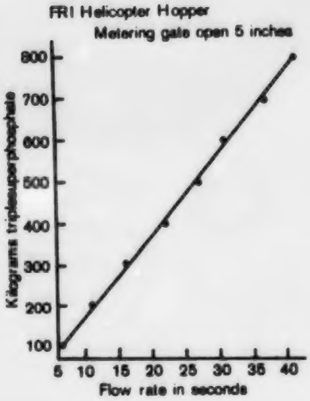


FIGURE 3: STATIC FLOW RATE

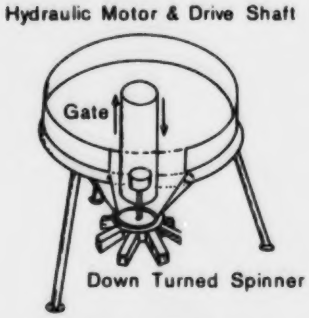


FIGURE 4: FRI HOPPER

4. A hopper gate "proportional controller" operates the movement of a cylinder gate inside the hopper. The flow-rate from the hopper is controlled by the vertical movement of this cylinder gate, which is infinitely variable between the fully opened and fully closed positions. The upper limit of travel can be set electronically to a fixed point, or automatically adjusted to maintain a preset kilogram per hectare flow-rate. This flow-rate is maintained by "taking" the ground speed information and using it, through the controller, to guide the adjustment of the cylinder.

In all modes, the cylinder gate can be fully opened by manual override to clear blockages in flight or to dump the load.

Before the introduction of a guidance system, application rates had been substantially increased to try to counteract uneven spread. The standard rate of application was almost doubled to 1200 kg/ha (single superphosphate applied once every 4-10 years) in an attempt to ensure that all parts of a plantation received at least 600 kg/ha of fertiliser.

CONCLUDING REMARKS

Current experience has shown that, with the guidance system, ground speed indication to the pilot, a ground-speed-guided hopper cylinder gate, and the FRI hopper, used in conjunction with well-granulated fertilisers, application rates can be reduced to between 200 and 500 kg/ha, with even fertiliser distribution which in turn will ensure even tree growth.

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BACILLUS THURINGIENSIS SPRAY DEPOSITION IN A PENNSYLVANIA OAK FOREST CANOPY

E. Alan Cameron[1] and Robert A. Fusco[2]

ABSTRACT — Dipel® was applied in late May as 8L (oil) formulations at 2.34 l/ha, or 6AF or 8AF (water) formulations at 2.34, 3.14, or 7.02 l/ha, for control of the gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Lymantriidae) in a central Pennsylvania oak forest with trees ca 18-25 m tall. A fixed-wing Piper Pawnee Brave aircraft, fitted with eight 'Mini' Micronair® AU5000 rotary atomizers, was used for application. Fluorescent orange Dayglow® powder was included in each of the spray formulations to facilitate monitoring of droplet deposition on foliage.

Leaves were collected by tree-climbers from the upper, mid, and lower crown, both from close to the bole and near the crown periphery. Spray deposit was visible when leaves were examined under blacklight in the laboratory. Droplet density per cm^2 on both upper and lower leaf surfaces was calculated after examination of leaf samples from four trees in each of two plots for each formulation and rate tested.

In general, droplet density was higher (as expected) in the top of the canopy, but droplets readily penetrated throughout; leaves closer to the bole frequently had higher droplet densities than those near the edge of the canopy. Water-based formulations produced higher droplet densities on leaves, regardless of the volumes applied, than oil-based ones. Droplet densities on the lower surfaces of leaves were proportionately higher when smaller droplets were generated; when 7.02 l/ha, which contained the largest droplets, was applied, proportionately fewer droplets impinged on the lower surfaces of the leaves. Artificial collectors (spray cards) gave a poor indication of coverage when compared with natural collectors (leaves). All formulations and rates applied gave acceptable foliage protection, and reduction of gypsy moth numbers.

RÉSUMÉ — Un traitement un Diepel^{md} a été effectué à la fin mai. On a utilisé des préparations 8L (dans l'huile) à raison de 2,34 L/ha ou des préparations 6AF ou 8AF (dans l'eau) à raison de 2,34, 3,14 ou 7,02 L/ha pour détruire la spongieuse *Lymantria dispar* (L.) (Lépidoptère: *Lymantriidae*) dans une forêt de chênes située dans le centre de la Pennsylvanie et dont les arbres ont une hauteur d'environ 18-25 cm. Pour le traitement, on a utilisé un avion Piper Pawnee Brave équipé de 8 turbopulvérisateurs pneumatiques "Mini" Micronair^{md} AU5000. On a ajouté de la poudre orange fluorescent Dayglow^{md} à chacune des préparations à pulvériser pour faciliter le contrôle du dépôt des gouttelettes sur le feuillage.

En grimpant aux arbres, on a cueilli des feuilles provenant des parties supérieures, moyennes et inférieures de la cime, près du fût et près de la préiphérie de la cime. Le dépôt était visible à l'examen des feuilles sous lumière noire au laboratoire. La densité de gouttelettes par cm^2 sur les surfaces inférieure et supérieure des feuilles a été calculées après examen d'échantillons de feuilles provenant de quatre arbres de chacune de deux parcelles, pour chaque préparation et chaque taux d'application.

En général, la densité de gouttelettes était plus élevée (comme prévu) dans la partie supérieure du couvert, mais les gouttelettes pénétraient facilement dans toute l'épaisseur du couvert; les feuilles près du fût présentaient fréquemment des densités de gouttelettes plus élevées que les feuilles situées en périphérie. Les préparations aqueuses produisaient des densités de gouttelettes plus élevées sur les feuilles, quel que soit le volume utilisé, que les préparations dans l'huile. La densité de gouttelettes sur la surface inférieure des feuilles était proportionnellement plus élevée lorsque des gouttelettes plus petites étaient formées; lorsqu'on utilisait un taux de 7,02 L/ha (taux correspondant aux gouttelettes les plus grosses), on constatait qu'il y avait proportionnellement moins de gouttelettes projetées contre la surface inférieure des feuilles. Les collecteurs artificiels (cartes) donnaient une moins bonne indication de la couverture que les collecteurs naturels (feuilles). Toutes les préparations et tous les taux utilisés ont donné une protection acceptable du feuillage ainsi qu'une réduction du nombre de spongieuses.

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During the last decade and more, the use of *Bacillus thuringiensis* (Bt) has increased substantially in forest protection programs in both the United States and Canada (e.g., Grimble and Lewis 1985 — contained papers; Anon. 1986). The gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Lymantriidae), generally considered to be the most serious defoliator of hardwood trees in the northeastern United States, devoured over 5.2 million ha of forested land in 1981. Populations suffered massive collapses in subsequent years, but the pest is increasing again; nearly 1 million ha were defoliated in 1986 in the United States. Almost 250,000 ha of forest were defoliated in Ontario, Canada, in 1985. The insect is well established in the American midwest. Widespread populations have been discovered in the state of Oregon; almost 100,000 ha were treated with Bt three times in each of two years in an effort to eradicate the species there (Cameron 1986).

When Bt has been the insecticide of choice for aerial application in gypsy moth or spruce budworm control programs, it normally has been applied at a volume of 7.02-9.35 l/ha (96-128 oz/ac). Many programs have used even higher volumes. Chemical insecticides, by comparison, are applied at rates such as 2.92 l/ha (40 oz/ac) (e.g., Sevin-4-Oil) or 9.35 l/ha (e.g., Dimilin) for gypsy moth, or 1.46 l/ha (20 oz/ac) (e.g., Fenitrothion) for eastern spruce budworm. Program costs are substantially increased when larger volumes must be applied, and more aircraft may be needed to cover treatment areas within available application time windows. If Bt spray volume could be reduced, while maintaining efficacy, Bt would become much more competitive economically.

Recent improvements in formulation technology have allowed production of Bt preparations with much higher potency per unit volume of neat material. This development suggests the possibility of maintaining efficacy with reduced volumes of material. With adequate deposition of spray throughout the canopies of trees to be protected, it is possible to spray undiluted Bt; this option avoids the possibility of mixing errors or complications during operational programs.

During the spring of 1987, we monitored deposition of individual droplets of Dipel®, applied as 8L (oil) formulations at 2.34 l/ha (32 oz/ac), or as 6AF or 8AF (water) formulations at 2.34, 3.14, or 7.02 l/ha (32, 43, or 96 oz/ac), to a central Pennsylvania oak forest for the control of gypsy moth. The gypsy moth is well-established in this area, and has just passed from the release to the outbreak phase in the current gradation. Efficacy of the treatments was also assessed.

METHODS AND MATERIALS

The experiments were conducted on the north-west-facing slope of Tussey Mountain, Centre County, PA, ca 15 km southwest of State College; elevation in the various plots ranges from ca 400-630 cm. Trees are predominantly second-growth oaks, including northern red (*Quercus rubra* L.), white (*Q. alba* L.), and chestnut (*Q. prinus* L.), with some red maple (*Acer rubrum* L.), sugar maple (*A. saccharum* Marsh.), birches (*Betula* spp.), shagbark hickory (*Carya ovata* (Mill.) K. Koch), and white ash (*Fraxinus americana* L.) among the other hardwood species present. Most trees are ca 18-25 m (ca 60-80 ft) in height. Defoliation caused by gypsy moth in 1986 was light (< 30%) to moderate (30-60%); overwintering egg mass numbers averaged almost 3950/ha (*ca* 1600/ac), numbers adequate to cause moderate to heavy (> 60%) defoliation during the spring and early summer of 1987.

On 22 May, when ca 10% of the larvae were in the first stadium and the remainder were almost evenly divided between second and third stadia, Dipel was applied to the test plots at rates and volumes such that the dose sprayed in each of the applications was 39.5 BIU's/ha (16 BIU's/ac). A Piper Brave aircraft (Figure 1), equipped with eight 'Mini' Micronair® AU5000 rotary atomizers (Figure 2), was used. Each of five formulations or rates of insecticide was applied to three separate plots, 16.2 or 20.2 ha (40 or 50 ac) in size, for comparison of efficacy; three untreated plots were reserved as checks. Fluorescent orange Dayglow® powder was included in each of the formulations to facilitate monitoring of droplet impingement on foliage.

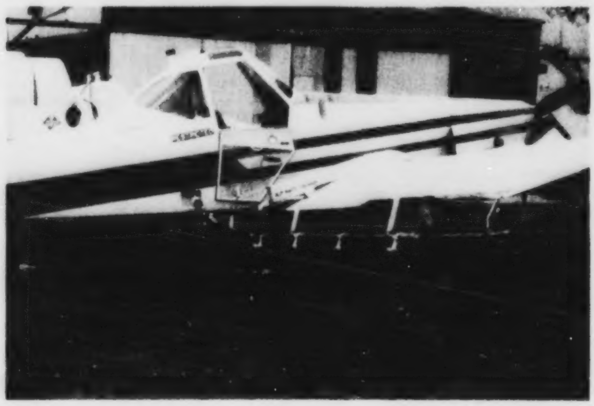

FIGURE 1: PIPER PAWNEE BRAVE AIRCRAFT (TALLMAN AERIAL SPRAYING) FITTED WITH FOUR 'MINI' MICRONAIR AU5000 ROTARY ATOMIZERS BEHIND EACH WING.

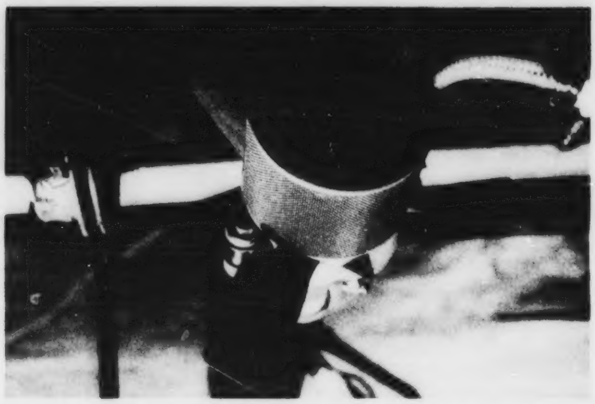

FIGURE 2: 'MINI' MICRONAIR AU5000 ROTARY ATOMIZER (MICRONAIR (AERIAL) LTD.) ATTACHED TO SPRAY BOOM. BLADE ANGLE DETERMINES SPIN RATE; SCREEN BREAKS UP SPRAY INTO DROPLETS.

Dipel 8L (oil-based), from two different production schemes (lot numbers 05-341-BJ and 04-022-BR), was applied first at 2.34 l/ha. The Micronair blades for these applications were set at 35° (45° for the inboard atomizer only on each wing to compensate for the higher air speed generated by the propeller), giving finer droplets than later applications at higher volumes. Air temperature was 14.5 - 19.5°C and winds were variable to 9 knots during application to these plots. Following thorough rinsing, water-based formulations were sprayed in the remaining treatments. Dipel 8AF (lot number 04-270-BJ) was applied first at 2.34 l/h; the Micronair blades remained at 35° (45° for the two inboard units), air temperature was 18°, and winds were variable to ca 8 knots. After changing the Micronair blade setting to 45° on all units, Dipel 6AF (lot number 04-271-BJ) was applied at 3.14 l/ha; temperature was 20°, with winds negligible to ca 5 knots. The final treatment, Dipel 6AF (same lot) at 7.02 l/ha, was applied with the Microair blades set at 55°; temperature remained at ca 20°, and winds were negligible to ca 8 knots. For the first four treatments, the VRU was set at 7; it was set at 11 for the last one. The spray aircraft was equipped with a Crop Hawk flow meter which enabled more precise control of the actual volume delivered.

Based on specifications for water-based formulations, Micronair blades set at 35° would have caused a spin rate of ca 9,000-10,000 rpm and given a droplet spectrum of ca 50-100 μ. A 45° setting should have produced ca 7,000-8,000 rpm and droplets of ca 75-125 μ, and a 55° setting ca 4,000-5,000 rpm and droplets of ca 125-200 μ. This latter setting generates droplets approximately the size of those obtained from flat fan nozzles in normal Bt applications.

Spray was allowed to dry on the foliage for a minimum of one-half hour before samples were collected. Professional tree climbers were asked to obtain branch samples with the aid of pole pruners from the upper, middle, and lower thirds of the crown of each of four trees, separated by at least 50 m, in the central portion of two of the three plots for each treatment; a total of 40 trees was sampled. In the middle and lower thirds of the canopy, one sample was taken from the inner portion of the crown near the bole, and a second was taken from near the crown periphery. Branch ends were put in water, and the foliage transferred to the laboratory for processing. Ten randomly selected leaves were removed from each branch, placed for protection in Minigrip® reclosable polyethylene bags so they did not overlap, and put into an ice chest in a 4°C cold room to be held until examined. Leaves so treated remained fresh much longer than test samples still attached to branches in water and held at room temperature. Had it been necessary, leaves could have been counted for up to three weeks after collection using our storage technique.

Ten oil or water sensitive spray cards (Tee Jet™, or Kromekote®) were placed on the ground at 20 m intervals on a line at right angles to the direction of application in eight of the ten plots from which foliage samples were to be taken. As they were picked up, each was labelled and placed for protection in a separate Minigrip bag until examined.

Five of the ten leaves in each sample were chosen for examination. The surface area of each leaf was determined using a Lic-Cor Portable Area Meter, Model LI-3000, which measured to 0.01 cm². Spray deposit spots fluorescing under a 20 W Sylvania Blacklight Blue F20T12 tube (Figures 3, 4) were counted against a black background in darkened room. A blackened 10 × 15 cm card, with a slit ca 0.65 cm wide cut longitudinally, was moved systematically across each leaf to facilitate counting. Since counting was done over a period of 10 days, individual droplets on the leaves could have changed size; consequentely, no attempt was made to distinguish among spot sizes or fluorescent intensity.

Spots were counted on both the upper and lower surfaces of each leaf examined. All counts were converted to spots/cm² for reporting purposes.

Efficacy of the various treatments was monitored by comparing overwintering egg mass counts with post-season counts, change in defoliation from that observed at the time of spraying until peak defoliation, and number of larvae and pupae counted beneath burlap bands placed around 24 trees in each plot, using the methods described by Cameron *et al.* (1983).

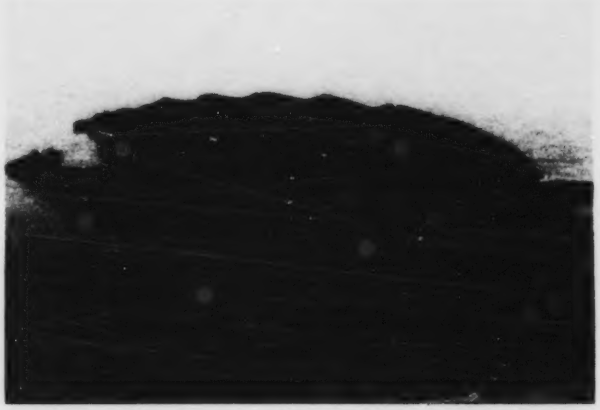

FIGURE 3: FLUORESCING DROPLETS ON A *Q. PRINUS* LEAF, UPPER SURFACE. TREATMENT WAS DIPEL 6AF @ 7.02 l/ha.

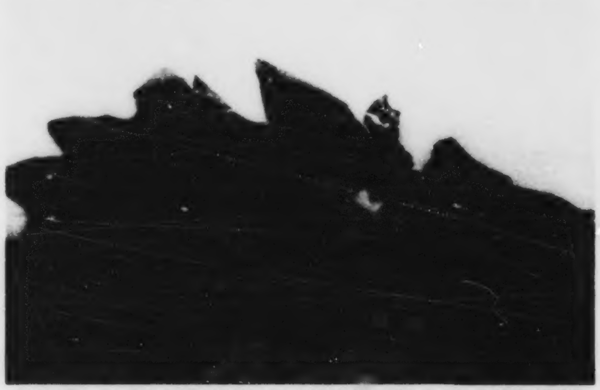

FIGURE 4: FLUORESCING DROPLETS ON A *Q. ALBA* LEAF, LOWER SURFACE. TREATMENT WAS DIPEL 6AF @ 3.14 l/ha.

RESULTS AND DISCUSSION

When data are summarized across all eight trees in the two separate plots monitored for each treatment, it is seen that, as expected, the greatest density of droplets is always in the 'top' samples (Figure 5). The formula

$$\frac{\text{total droplets, upper surface + total droplets, lower surface}}{\text{area of leaf}}$$

was used to calculate the densities, since larvae (at least beyond the second stadium) consume both upper and lower 'surfaces' of the leaves. Each open bar represents 40 leaves, except in a few cases where samples were missing or incomplete; the shaded bars normally represent 200 leaves, i.e., all leaves examined in each treatment.

There is a general trend, but with exceptions, for droplet density to decrease in the lower portions of the canopy. This is less pronounced with the 8L (oil-based) formulations than with the 6AF or 8AF (water-based) formulations. Even with the tendency for droplet density to decrease, there was still an average of over 2.8 droplets/cm² throughout the canopy in all of the AF applications, a density higher than any of the strata monitored under 8L applications. Clearly, spray droplets penetrated throughout the canopy, whether they were in the smaller or larger size ranges generated by the atomizers. In fact, there was better penetration,

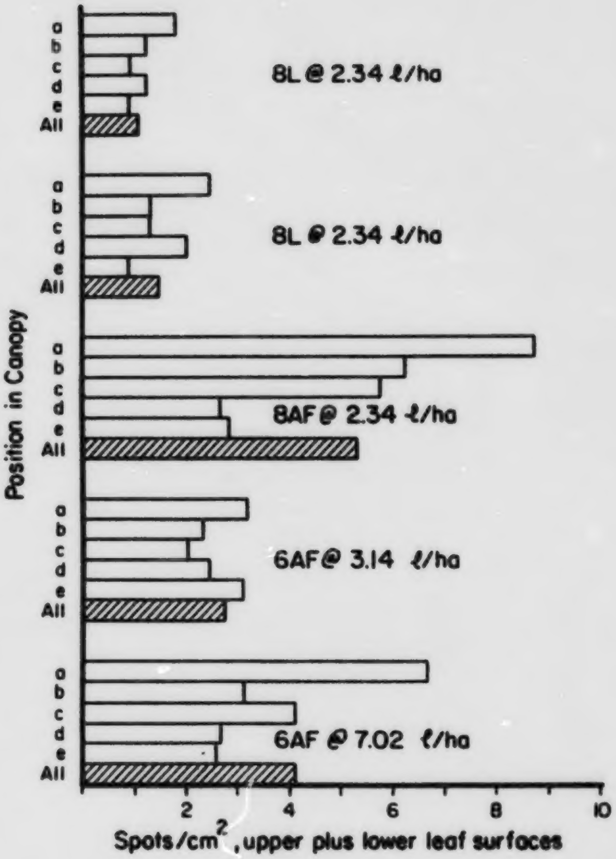

FIGURE 5: DROPLET DENSITY ON UPPER AND LOWER SURFACES OF LEAVES, ACCORDING TO FORMULATION AND VOLUME APPLIED AND POSITION IN THE CANOPY: UPPER THIRD (a); MIDDLE THIRD, INNER PORTION (b); MIDDLE THIRD, OUTER PORTION (c); LOWER THIRD, INNER PORTION (d); LOWER THIRD, OUTER PORTION (e), AND ENTIRE TREE (ALL).

and a higher density of spots throughout the whole canopy, in the 8AF application — which had both the smallest droplets (50-100 μ) and the lowest total volume (2.34 l/ha) of the water-based formulations.

Anticipated droplet size spectra obtained at different settings of the Micronair blades is based on charts from calibrations done with water formulations. Depending on the particular formulation being sprayed, these spectra will vary. The specific gravity of the 8L (oil) formulations used was 0.96; the AF (water) formulations had a specific gravity of 1.18. We believe that the increased weight (by over 23%) of the AF formulations caused much more drag on the rotary atomizer cages than did the lighter 8L formulations. As a consequence, the cages actually spun faster and created finer, lighter droplets from the 8L formulations. This would account for both apparent anomalies we observed when comparing those formulations applied at 2.34 l/ha. First, there was more even coverage throughout the entire canopy from the 8L applications as the very light droplets were wafted about on even the slightest breeze; second, reduced droplet density might be a consequence of too fine a breakup of the material and drift of a part of the spray away from the target area. Use of tachometers on the rotary atomizers would give precise information on the rpm's of the atomizers, and allow adjustment as necessary to change the droplet size spectrum. More detailed characterization of droplet diameters generated from various formulations and at different blade angles is required further to refine application technology.

Data presented in Figure 6 indicate that substantial numbers of droplets impinged on the lower surfaces of leaves. The three volume and formulation combinations illustrated allow comparison of an 8L formulation at 2.34 l/ha, and AF formulations at 2.34 and 7.02 l/ha. Proportionately more droplets per cm² impinged on upper surfaces of leaves treated at 2.34 l/ha with the 8AF formulation than with the 8L formulation (ratio for upper surface; lower surface, 2.48: 1.00 for 8AF, 1.23: 1.00 for 8L). Concentration of droplets on the upper surface was magnified even more when the 6AF formulation was applied at 7.02 l/ha; the ratio increased to 3.33: 1.00.

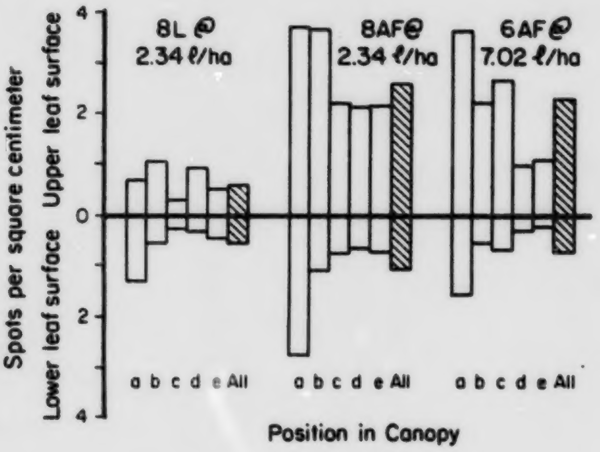

FIGURE 6: DROPLET DENSITY ON UPPER VS. LOWER SURFACES OF LEAVES, ACCORDING TO FORMULATION AND VOLUME APPLIED (NOT ALL PLOTS INCLUDED) AND POSITION IN CANOPY. KEY AS IN FIGURE 5.

The same consideration described earlier, namely, that smaller, lighter droplets are wafted about more readily, would also explain these results. Thorough penetration of the canopy by many smaller droplets increases the likelihood that they might impinge on lower leaf surfaces as they float in eddy currents within the crowns of the trees.

When Bt is applied conventionally using flat fan nozzles, the individual droplets are at least as large as those in our highest volume application (125-200 μ), and often include droplets up to 400 μ or more (eg., Yendol 1985). Such large droplets are much less efficient. We would expect even less likelihood of large droplets penetrating throughout the canopy and impinging especially on the lower leaf surfaces. Early in the season, when most of the small larvae are feeding on the under sides of leaves, efficacy of such treatments would be expected to be diminished. This could explain the common need for two applications of Bt in programs using flat fan technology and targeting the first application at first and early second instar larvae.

Droplet impaction on artificial collectors (spray cards) deployed at ground level did not correlate with information obtained by counting droplets on the natural targets (leaves) (Table 1). In our tests, densities recorded from analysis of cards ranged from 29% to 158% of the densities on the upper sides of leaves taken from trees in the same plots. Similar lack of correlation has been reported in Bt spray applications made against pests on conifers (eg., Fast *et al.* 1985).

TABLE 1: Droplet density per cm^2 on upper surfaces of leaves and on artificial collectors, Centre County, PA 1987

Treatment	Droplets per sq cm		Ratio, Leaves: Collectors
	Leaves	Collectors	
Dipel 8L[1] @ 2.34 l/ha	0.709	0.557[5]	1.00: 0.79
Dipel 8L[2] @ 2.34 l/ha	1.254	1.779[5]	1.00: 1.42
Dipel 8AF[3] @ 2.34 l/ha	5.269	1.542[6]	1.00: 0.29
Dipel 6AF[4] @ 3.14 l/ha	1.525	2.409[6]	1.00: 1.58
Dipel 6AF[4] @ 7.02 l/ha	3.235	2.854[6]	1.00: 0.88

[1] Lot no. 05-341-BJ
[2] Lot no. 04-022-BR
[3] Lot no. 04-270-BJ
[4] Lot no. 04-271-BJ
[5] Tee Jet cards
[6] Kromekote cards

All of the various Bt treatments gave efficacious control of the gypsy moth, based on foliage protection (Table 2). A preliminary assessment of larval, pupal, and egg mass data support our judgement of efficacy. Clearly, a single application with a delivered volume at least as low as 2.34 l/ha of neat material, if properly applied using available technology, will produce acceptable levels of foliage protection and population reduction in situations where moderate to heavy defoliation can reasonably be expected. This conclusion contrasts starkly with recent recommendations of Abrahamson and Eggen (1985), suggesting that multiple Bt applications or chemical insecticides are necessary in high building populations (>400 large egg masses/ha), and that delivered volumes must be 7.02 or 9.35 l/ha. Single applications were recommended only in areas with a declining population, or in areas with building populations having <400 egg masses/ha. The kinds of studies we have described (noted, incidentally, by Abrahamson and Eggen as needed) will permit more efficient use of Bt.

TABLE 2: Gypsy moth defoliation estimates, Centre Country, PA 1987

Treatment	At treatment	At peak	Change
Dipel 8L[1] @ 2.34 l/ha	1.13[5]	1.47	+ 0.34
Dipel 8L[2] @ 2.34 l/ha	1.08	1.53	+ 0.45
Dipel 8AF[3] @ 2.34 l/ha	1.32	1.32	None
Dipel 6AF[4] @ 3.14 l/ha	1.28	1.46	+ 0.18
Dipel 6AF[4] @ 7.02 l/ha	1.05	1.33	+ 0.28
Check	1.11	2.60	+ 1.49

[1] Lot no. 05-341-BJ
[2] Lot. no. 04-022-BR
[3] Lot no. 04-270-BJ
[4] Lot no. 04-271-BJ
[5] Each number represents the average of 3 estimates by each of two observers at each of 6 points in 3 different plots per treatment, i.e., 108 individual estimates per treatment. Defoliation was estimated in 20% increments, with 1 = 0-20%, 2 = 21-40% . . . 5 = 81-100%.

One of the thrusts in Bt formulation improvement is production of even higher potency formulations than are currently available. This suggests that even lower volumes of delivered spray might be just as efficaceous, assuming good distribution of droplets throughout tree canopies. Among the chemical insecticides, the use of Dimilin is increasing considerably in the United States; Sevin has been almost entirely eliminated from federal and state gypsy moth programs, although it is still widely used by private applicators. The most common application volume for Dimilin is 9.35 l/ha, compared with 2.92 l/ha for Sevin. Assuming acceptable efficacy from Bt treatments, and ignoring the use of environmental hazards of chemicals vs. biologicals, the economics alone of treating four times as much area with the same volume of material would be a powerful argument to make Bt the insecticide of choice for forest protection programs. Fewer spray aircraft would be required to complete contracts within sometimes narrow spray windows, which would facilitate contracting operations.

We have demonstrated efficaceous results with Dipel against the gypsy moth, using both neat 8L formulations, and AF formulations sprayed either neat or diluted with water to increase spray volume; we can describe droplet impingement on leaves throughout the canopy of oaks. We believe that there is considerable promise for improvement in delivery of ultra low volumes of Bt, using existing technology such as rotary atomizers instead of flat fan nozzles, for control of gypsy moth infestations in hardwood forests. Application of neat materials has many handling advantages; economies can be realized especially in large spray programs. With continued efforts to understand and improve the technology associated with spraying Bt, and retention of efficacy at even lower application volumes, the future of this material in forest protection programs is secure.

ACKNOWLEDGEMENTS

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MICROCOMPUTER PLANNING MODEL IMPROVES EFFICIENCY IN AERIAL SPRAY PROJECT

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1. INTRODUCTION

While the spruce budworm poses a severe threat to spruce-fir forests of Canada and the northern United States, the threat to mature stands of economically valuable trees can be contained by yearly spraying. Our emphasis is in the efficiency of the aerial spray program. In Maine, insect control requires spraying nearly a million acres of remote forest within a two to four week insect vulnerability window. The spraying is accomplished by using up to 30 aircraft flying from 8 airfields to spray 300 to 400 treatment areas (spray blocks).

Prior to 1983, decisions on airfields and aircraft teams were made in the following manner. The spray blocks (treatment areas) were plotted on a large map of Maine, circles were drawn around potential airfields corresponding to the operating range of aircraft, and spray blocks were assigned to airfields and aircraft teams based on the observed patterns and subjective judgement. Aircraft teams were limited to a maximum number of acres based on previous experience.

The authors began work with the Spruce Budworm Suppression Project in 1983 in an attempt to reduce operating costs for the spray project. During 1983, a linear programming (LP) model was developed and tested. The model minimizes total aircraft operating cost (fuel, depreciation, maintenance and pilot salaries). The model was used in planning the 1984 and 1985 projects (Rumpf et al. 1985). It explicitly considers distance limitations, flying cost for each aircraft type, time windows (time available for effective spraying), and insecticide requirements. The output of the model is the least-cost set of flight plans, i.e. aircraft-block-airfield combinations. The same model was adapted in 1985 to run on a microcomputer for use by the staff of the Maine Forest Service at its offices in Augusta, Maine.

In this paper, we first present, a description of the problem, then we present the LP and the resulting microcomputer-based model and finally we discuss the model use and results for the 1983 through 1985 projects.

2. DESCRIPTION OF THE PROBLEM

Yearly spraying of treatment acreage takes place during May and June; the infested areas are located in remote, northern and eastern Maine. Aircraft, crews, and support personnel are stationed at each of the airfields. Only eight fields were suitable for use during the 1985 project. Aircraft teams consisted of one or more spray aircraft, a guide plane with pilot and navigator and a monitor plane with pilot and observer. The navigator used LORAN, a radio wave location system, to determine exactly when to start and stop spraying. Several teams of aircraft may be stationed at an airfield; for example, in 1983, four C-54 teams, one M-18 team, and two Thrush teams were based at Presque Isle, the most active site. The Thrush or Air Tractor is a workhorse of the agriculture spray industry. A single engine aircraft, it flies slowly, has a short range but provides very accurate spraying; it flies as a team of three aircraft. The M-18 is a large single engine aircraft with longer range and larger payload than the Thrush which can also apply spray very accurately; it flies as a team of two aircraft.

Project planning begins in the fall with aerial and ground analysis of insect danger. The state, in cooperation with landowners, makes a preliminary determination of acreage requiring treatment. While the Maine Forest Service coordinates the operation, spraying activities are subcontracted. A spray operator employing agricultural pilots performs spraying; another contractor performs chemical mixing and delivery. Bid specifications are prepared during January, are received by the end of February, and the contracts awarded by March. The Forest Service develops operational plans, works out logistics with the subcontractors, decides when blocks can be sprayed, and monitors every spray trip to insure effectiveness and environmental protection.

The weather is an important factor. The insecticide attains effective dispersion and deposit on tree foliage only under dry conditions and moderate wind speeds of three to fifteen miles per hour. These requirements generally restrict spraying to early morning or evening hours. The spraying must also occur during a specific stage of insect development, a requirement which limits spray activity to a period of three to seven days for a given site (spray block). Airfields are used for a period of two to four weeks depending on the number and location of blocks sprayed. Total project duration for all airfields is from three to six weeks.

In 1983, 24 spray aircraft, operating from 6 separate air-strips in northern and eastern Maine, sprayed nearly 850,000 acres. The contracting costs for the aircraft and crews represent one third or more of total costs for the project each year.

3. LINEAR PROGRAMMING (LP) MODEL

Linear programming is a well known technique (Hillier and Lieberman, 1986) for which efficient optimizing algorithms exist. The technique has been applied to several forest planning problems (Dykstra, 1984). If a problem can be described by linear equations for a set of decision variables, then a linear objective function can be uniquely solved for the best solution. In our case, the objective is to minimize the cost of spraying while insuring that all required spraying is accomplished.

A mathematical flying time model was needed to estimate the flying time required for alternative combinations of aircraft, airfields, and spray blocks. The parameters for time spent actually spraying and for total flying time were derived by splitting the total aircraft time allocated to a block into several task times.

The spray time model, assuming the spray capacity of the aircraft exactly equals the area of the spray block, is:

t_{ijk} = ferry time + orientation time + spraying time + turning time + flying time over "outs"

Thus,

$$t_{ijk} = 2(d_{jk}/f_j) + to_i + a_j/s_i$$

$$+ ([ew_j/sw_i - 1]) (ta_i)$$

$$+ (n_j/(l\text{-}n_j)) (a_j/s_i)$$

Where ew_j is the east-west distance of block j, and f_i and sw_i are the ferry speed and swath width of the ith type of aircraft. Definition of other variables is given in Appendix A. The notation [] indicates that the least integer upper is taken for the number of swaths of a block (ew_j/sw_i - 1). Thus, the total number of turns equals the number of trips across the block minus 1. A trip across a block has always a N-S direction. For a project of 250 spray blocks, about 800 t_{ijk} are feasible while only 250 are chosen for the optimal solution.

If the area of the spray block is less than a full load, ferry time is multiplied by a fraction, equal to a_j/l_{ih}. If the block is larger than spray capacity, ferry time, and orientation time are multiplied by a_j/l_{ih}, and then ground time (g_i) times $[a_j/l_{ih} - l]$ is added. Note, spraying time, time over "outs," and turning time already are adjusted for size of block. In this way, the spray time model is adjusted for varying size of spray block. The final adjustment in the total time is division by 0.90, efficiency correction factor. This factor adjusted for deviations from normal procedures. The size of the correction factor was decided based on the operations manager's recommendations.

The linear programming (LP) formulation is given in Appendix B. Given a set of airfields and the characteristics of the different types of spray aircraft, the LP model determines the lowest cost set of flight plans which will accomplish the required spraying. The ability to evaluate alternative scenarios, for example, the effect of closing certain airfields or using a different type of spray aircraft, is one major advantage of the model.

The decision variables are the times allocated to each aircraft team flying out of each airfield to spray each block. Each time includes spraying time, turning time, void time, orientation time, ferrying time, and ground time. If less than a full load of insecticide is used for a block, only a proportional part of ferrying and ground time is allocated to that block. Only the variables which can be identified with feasible flight plans, that is allowable combinations of blocks, aircraft, and airfields, are considered (Appendix B, equation [2]). An allowable combination is such that the block is within the operating range of the aircraft flying out of a particular airfield, the aircraft is allowed to spray the insecticide specified for the block, and there are one or more aircraft teams of the type specified stationed at the airfield. For the spray project in Maine, each spray block had 2 to 4 feasible flight plans.

Two types of constraints are imposed on the variables. First, (Appendix B, [3]), the time used exclusively for spraying each block should be sufficient to guarantee complete spraying, and that time depends on the location and geometry of the block and the aircraft and airfield characteristics. The second type of constraint (Appendix B, [4]) takes into consideration the limited time window for each aircraft and airfield combination during which weather conditions and pest development allow for effective spraying. The function to be minimized is the total spraying cost. The objective function (Appendix B, [1]) sums spraying cost for all chosen flight paths. The decision variable, time allocated to spray the block, is multiplied first by a ratio representing actual flying time over total time (flying and ground) then by total cost per flying hour. The total cost per flying hour includes both fixed and variable costs for an aircraft team (see Appendix A). An optimal solution has the m positive t_{ijk} (the remaining $t_{ijk} = 0$) which provide the least cost value of the objective function.

4. THE MICROCOMPUTER PLANNING MODEL

The LP model was found very useful in preparing bid specifications and planning for aircraft and airfield location during the 1984 Spruce Budworm Spray Project. However, the need for user-friendly software which requires shorter execution times and would always be available at the Maine Forest Service offices became apparent after using the LP model for one year. Easy data entry, error recovery, editing of input data and quick evaluations of many possible scenarios were achieved by adapting the LP model for the microcomputer and supplementing it with data entry and report writing software.

The adaptation of the LP model resulted from the realization that the time window constraints (Appendix B, [4], insuring that no aircraft team was assigned to spray more hours than the historically determined time window) could be relaxed with no loss of validity. In effect, the model could be used to determine the number of teams (or hours) needed rather than setting limits before running the model. Relaxation of these time constraints decreased the computer time required to solve the problem by more than tenfold and thus allowed solution on a microcomputer in an elapsed time of less than 10 minutes for a 220 block, 5 airfield, 3 aircraft team problem. The analysts modified the model to work on an IBM-PC microcomputer rather than the Digital minicomputer or the IBM mainframe computer used previously. The final version ran on the Maine Forest Service's Burroughs Model B-25 microcomputer using an MS-DOS (IBM-PC) emulator package. The Burroughs version of the software passed between analysts and project staff three time before final approval.

The microcomputer spray model was designed in modular form: one program developed for data entry; the LP module; and a third program which used the output from the modeling algorithm to prepare both summary and detail reports on cost and flight paths. All programs were written in FORTRAN. The data entry and the report program went through several revisions until a satisfactory functional level was obtained.

We collected data on orientation time, turning time, ground time, and efficiency during the 1983 spray operation. We measured the east-west distances and the percent "outs" on the map. The "outs" are marshes or other wetlands which are not sprayed. The Maine Forest Service provided the remaining data such as ground time, flight speed, and spray speed.

5. MODEL USE AND RESULTS

The LP model was first used in analyzing the 1983 project. The main emphasis was demonstrating that the model accurately represented the aerial spray project. The project staff reviewed results and confirmed model accuracy. Active model use in planning began with the 1984 project. Planning for 1984 was complicated by the closing of a centrally located airfield and availability of a new type of aircraft characterized as a long-range single engine (LRSE) such as the Agcat B with long-range gas tanks or the Bull Thrush. While evaluating the 1983 project, we found that cost increased by 20 percent when access to the centrally located airfield was lost. Although the airfield decision could not be changed, the results suggested the possibility of airfield construction as an economic option should the desired airfield continue to be closed in the future.

The 1985 project was evaluated using the microcomputer model resident in the spray project manager's office. The project consisted of 220 blocks and a decision was made to use Thrush, M18 and C54 aircraft for the project. Again a major consideration was which airfields to use. The procedure can be demonstrated by referring to Table 1. The summary report of the model is provided for two alternatives: 8 airfields and 5 airfields. The operating cost increases by about $8,000 for the 5 airfield alternative. The use of C54 and M18, the longer range aircraft, increases for the 5 airfield alternative but the overall project cost is less expensive for the 5 airfield case when the $30,000 cost of opening 3 additional airfields is taken into account. Portions of Reports 2 and 3 are provided in Table 2. These reports provide specific flight plan information for each spray block and thus provide the data required for detailed planning. The examples provided in Table 2, Report 3 include many multiple block trips for the C54, the large 4 engine aircraft.

TABLE 1: Comparison results for 1985 spruce budworm project

Summary Report 1 — Eight airfields

Total cost $434,450.20

	Flying hours		
	Aircraft team		
Airfield	**M18**	**C54**	**Thrush**
Old Town	5.47	.00	24.02
Presque	.65	131.05	5.26
Ragmuff	3.80	.00	70.68
Rangeley	1.93	.00	4.75
Estcourt	.00	.00	7.51
Red Pine	.00	.00	32.42
Greenvil	.00	.00	.00
Millinoc	3.57	.00	9.80
Total per team	15.42	131.05	154.44

Summary Report 1 — Five airfields

Total cost $442,72.20

	Flying hours		
	Aircraft team		
Airfield	**M18**	**C54**	**Thrush**
Presque	.65	139.87	5.26
Ragmuff	3.80	.00	70.68
Rangeley	1.93	.00	4.75
Red Pine	.00	.00	32.42
Millinoc	27.57	.00	18.33
Total per team	33.95	139.87	131.44

A summary of actual costs for 1983 to 1985 is presented in Table 3. The amount of endangered forest declined dramatically during these three years. This was due to intensive harvesting of the mature stands (the preferred habitat of the budworm) and consequent decline in budworm population. Based on computer model results, the project/staff was able to lower the number of aircraft even more rapidly than the decline in endangered acres of forest.

TABLE 2: Detail reports, 1985 spruce budworm project

Report 2 — Allocations by airfield and aircraft to blocks

Airfield	Aircraft	Block	Acerage	Chemical
Presque	C54	A001	1170	Zectran
Presque	C54	A010	2363	Bt
Presque	C54	A012	864	Zectran
Presque	C54	A015	474	Zectran
Presque	C54	A026	7729	Bt
Ragmuff	Thrush	E036	476	Zectran
Ragmuff	Thrush	E041	1991	Zectran
Ragmuff	Thrush	E042	518	Zectran
Ragmuff	M18	F020	2639	Zectran
Ragmuff	Thrush	F022	614	Zectran
Rangeley	Thrush	H007	2370	Bt
Rangeley	Thrush	H008	2945	Bt
Rangeley	M18	H013	4023	Bt
Rangeley	Thrush	H031	200	Bt
Rangeley	Thrush	H032	770	Bt
Rangeley	Thrush	H034	2400	Bt
Red Pine	Thrush	A028	928	Zectran
Red Pine	Thrush	A050	784	Zectran
Red Pine	Thrush	A053	525	Zectran

Report 3 — Flying hours for blocks

Block	One way Ferry D	Ferry T	T on block	T for 1 trip	Full load req
A001	77.00	.43	.36	.36	.09
A002	74.55	.41	.28	.28	.07
A003	74.75	.42	.46	.46	.13
A004	75.13	.42	.30	.30	.12
A005	74.30	.41	.65	.65	.57
A006	66.09	.37	.26	.26	.08
A010	73.37	.41	.57	.57	.30
A012	70.17	.39	.27	.27	.07
A015	67.70	.38	.26	.26	.04
A026	75.84	.42	1.28	1.28	.97
A027	76.74	.43	.61	.61	.27
A028	30.78	.28	.39	.39	.18
A041	78.74	.44	.68	.68	.38

D = Distance in miles
T = Time in hours

TABLE 3: Spruce budworm aerial spray program cost data

	Year		
	1983	1984	1985
Cost	$1,445,923	$1,166,057	$724,600
Inflation Adjusted Cost*	1,445,923	1,118,413	670,926
Acres	846,382	668,026	410,909
Inflation Adjusted Cost per Acre	$1.71	$1.67	$1.63
Number of Aircraft			
Single engine	20	16	10
multiple engine	4	4	0
Total	24	20	10

* In 1983 dollars; adjusted by Consumer Price Index.

The net result was a small decline in inflation adjusted cost per acre. Note that economy of scale considerations would lead one to expect cost per acre to increase as the size decreased while use of the model actually lowered cost per acre.

The overall cost of developing a user friendly model was about $18,000. This included a contract for $15,000 with the analysts through Northeastern University and an additional $3,000 in staff support costs required for cost analysis and training time. Savings can be estimated by considering the 1983 project. The project used 4 C54 aircraft teams and 7 small aircraft teams flying from 7 airfields to spray over 300 spray blocks. The model solution would have required one less aircraft team at a savings of over $40,000 in fixed cost with additional savings in variable costs.

Several general suggestions can be drawn from our experience with the aerial spray model. First for geographically dispersed spray areas, long-range aircraft use combined with opening fewer airfields is more efficient. Centrally located airfields will cut costs. Marginally endangered blocks should be held aside until an evaluation of the remainder of the project is complete. At that time, the marginal blocks can be included if their inclusion does not require additional airfields or spray teams and the associated jump in fixed costs.

SUMMARY AND CONCLUSIONS

The authors, working with the Maine Forest Service staff in a cooperative effort, developed a LP mathematical model to improve operational efficiency of the Spruce Budworm Spray program. The least cost solution of the model provides the set of flight plans (aircraft, airfield, spray block assignments) which accomplish the required spraying.

This application provides an illustration of applying mathematical modeling to improve operational management. The Maine Forest Service found the model useful in lowering spray operation costs [Rumpf et al, 1985].

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APPENDIX A

Definitions and Estimation of Cost per Flying Hour

Definition of Variables for LP Models

(i,j,k) flight plan denotes the assignment of aircraft type i to fly from airfield k to spray block j

n,m,p, are the number of aircraft types, blocks and airfields

t_{ijk} is a decision variable representing the aircraft time required for the (i, j, k) flight plan

g_i = ground time (required to refuel and load insecticide) for aircraft i

l_{ih} = area sprayed by aircraft team i fully loaded with insecticide type h

to_i = orientation time required by team type i, the time required at the spray block to obtain direction and formation required to begin spraying.

n_j = proportion of "outs", the area within the boundaries of the spray block j which is not sprayed (usually streams and marshes).

A_k = is the set of aircraft types allowed to be stationed at the airfield k

G_i = is the set of insecticides allowed to be sprayed by aircraft type i

C_i = is the total cost charged per hour of flying aircraft team type i; C_i includes fixed cost prorated over D_i plus variable cost V_i

s_i and or_i are spray speed in acres per hour and operating range of aircraft type respectively

a_j and h_j are the area and the insecticide type corresponding to block j

d_{jk} is the distance between block j and airfield k

S is the set of feasible flight plans;

S = $\{(i, j, k):(d_{jk} < or_i) \text{ and } (h_j\ G_i) \text{ and } (i\ A_k)\}$

T_{ik} is the total time window available including all teams of type i stationed at airfield k

u_{ijk} is the fraction of flying time over the sum of all task times for the (i,j,k,) flight plan

r_{ijk} is the fraction of spraying time over the sum of all task times for the (i,j,k) flight plan

Cost per Flying Hour

Specific cost data for one type of aircraft are listed to illustrate what is required. A full set of data is available (see Rumpf et al, 1985)

THRUSH

Three-plane spray team, plus one guide plane with pilot and guide, one spotter Fixed Costs

— fly up to 1500 miles at $2000/plane	$ 6,000
— 3 pilots for 1.5 months	18,000
— guide plane lease	3,000
— guide pilot	6,000
— guide	3,000
— spotter	3,000
— one/half contractor representative	3,000
— food/lodging 8.5 people, 45 days, $22/day	8,400
— transportation	500
	$50,900

Flying time available (D_i) for Thrush team estimated at 55 hours

Fixed cost per hour	$ 925
Variable Costs	
— depreciation at $100/hour, 3 planes	300
— fuel, 3 planes at 40 gal/hour, 1 at 10	260
— maintenance, 4 planes at $20/hour	80
Total cost/hour for Thrush team	$ 1,565

APPENDIX B
Linear Programming Model

[1] $$\text{Min} \sum_{(i,j,k)\ S} C_i u_{ijk} t_{ijk}$$

subject to

[2] $$S = \{(i,j,k) : d_{jk} \leq or_i \text{ and } h_j \varepsilon G_i \text{ and } i \varepsilon A_k\}$$

[3] $$\sum_{k=1}^{P} \sum_{i \varepsilon A_k} s_i r_{ijk} t_{ijk} > a_j \qquad j = 1, \ldots, m$$

[4] $$\sum_{j=1}^{m} t_{ijk} < T_{ik} \qquad \begin{array}{r} k = 1, \ldots, p \\ i = 1, \ldots, n \end{array}$$

[5] $$t_{ijk} > 0 \qquad (i,j,k)\ S$$

COMPARING ATOMIZATION CHARACTERISTICS OF SOME *BACILLUS THURINGIENSIS* AND DIFLUBENZURON FORMULATIONS

A. Sundaram[1], A.G. Raske[2], R.J. West[2], A. Retnakaran[1]

ABSTRACT — The viscosity of a diflubenzuron (Dimilin®) formulation changed only slightly with increasing shear rate, but the viscosity of the two *B.t.* formulations, Futura XLV® and Thuricide 48LV® decreased rapidly. Diflubenzuron had Newtonian characteristics and the two *B.t.* formulations exhibited pseudoplastic behaviour. The surface tensions of all three formulations were similar. Diflubenzuron vaporized decidedly faster at 2.45%/minute than did the *B.t.* formulations at 1.65% to 1.75%/minute.

Field tests confirmed laboratory data in that spray deposits of diflubenzuron had a larger proportion of small droplets on the target than either Futura XLV or Thuricide 48LV. However diflubenzuron sprays also formed a few large droplets that contained relatively large proportions of spray volume. Futura XLV and Thuricide 48LV had narrow droplet spectra and most of the spray volume arrived at the canopy in the desired small-diameter droplets.

RÉSUMÉ — L'augmentation du taux de cisaillement n'a que légèrement modifié la viscosité d'une préparation de diflubenzuron (Dimilin®), contrairement à celle de deux préparations de *B.t.*, Futura XLV® et Thuricide 48LV® qui a diminué rapidement. Le diflubenzuron présentait des caractéristiques newtoniennes et les deux préparations de *B.t.* avaient un comportement pseudoplastique. La tension superficielle des trois préparations était similaire. Le diflubenzuron s'atomisait nettement plus rapidement à 2,45% par minute que les préparations de *B.t.* à 1,65 à 1,75% par minute.

Des essais sur le terrain ont confirmé des données obtenues en laboratoire: en effet, la bouillie de diflubenzuron s'est déposée en petites gouttelettes beaucoup plus nombreuses que le Futura XLV ou le Thuricide 48LV. Par contre, les bouillies de diflubenzuron ont également produit quelques grosses gouttelettes qui contenaient des pourcentages relativement élevés (volume) du produit pulvérisé. Les spectres de grosseur des gouttelettes de Futura XLV et de Thuricide 48LV étaient restreints et la bouillie atteignait généralement le couvert sous la forme désirée de petites gouttelettes.

INTRODUCTION

The efficiency of ultra-low-volume spraying of pesticides against forest insects is maximized when a large proportion of the spray volume is contained in droplet sizes of 70 μm to 100 μm diameter (Himel and Moore 1969; Barry and Ekblad 1978; Sundaram 1982). These droplet sizes have a high probability of impinging upon tree foliage. The presence of many droplets greater than 100 μm leads to inefficient use of sprayed material because these droplets contain relatively large volumes. Physical properties of pesticide formulations, such as viscosity, volatility and surface tension affect atomization and droplet evaporation, and therefore droplet spectrum (Sundaram *et al.* 1985a; 1985b).

We studied the relationship between some physical properties of two *Bacillus thuringiensis* (= *B.t.*) formulations and one formulation of the insect growth regulator diflubenzuron with their resultant droplet size-spectra after aerial application.

MATERIALS AND METHODS

All three insecticides used were commercial water-based formulations. The formulations of *B.t.* were Futura XLV® (Chemagro Ltd.) and Thuricide 48LV (Zoecon Corp.), and the commercial formulation of diflubenzuron was Dimilin WP-25® (Duphar BV), a wettable powder sprayed at 30 g ai/ha (Table 1). The dye Erio Acid Red (Ciba Geigy), was added to *B.t.* formulations at 0.5% and to diflubenzuron at 1% of weight to volume.

TABLE 1: Dosages, rates of application and weather parameters during aerial application of formulations in Newfoundland in 1985.

Parameter	Futura XLV	Thuricide 48LV	Diflubenzuron
Dose	30 BIU/ha	30 BIU/ha	30 g ai/ha
Emission rate (ℓ/m)	21.5	24.2	20.8
Volume rate (ℓ/ha)	2.1	2.36	2.0
Temp. °C	14	17	16
Rel. Hum. (%)	74	74	76
Wind speed (km/h)	5-12	4-7	3-5

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1) Canadian Forestry Service, Forest Pest Management Institute, Sault Ste. Marie, Ont.

2) Canadian Forestry Service, Newfoundland Forestry Centre, St. John's, Newfoundland.

Viscosity shear-rate relationship and surface tension of formulations were measured with standard procedures. Volatility was determined by a gravimetric method (Sundaram and Leung 1986). Droplet volatility was expressed as percent weight loss/minute and in half-life ($T^{1/2}$, min.) of evaporation; the time for the volatile droplet component to evaporate to half of their initial values.

Each formulation was sprayed on a 15 ha plot in 1985 in Newfoundland by a Piper Pawnee aircraft equipped with six Micronair AU 5000 atomizers. The blade angle of the Micronairs was set at 35°. Air speed was 160 km/h and a 40 m swath width was used in spray-volume calculations.

Kromekote® cards, 10 cm × 10 cm in size, and two glass plates each 7.5 cm × 5.0 cm in size, placed about 30 cm above the ground at 15 m intervals across the plot (n = 21) before spray time, were used to measure spray deposit reaching the ground. These cards and plates were collected within 60 min. after the application. Kromekote cards were analyzed for droplet density, droplet diameter and droplet volume (Sundaram *et al.* 1985b; Himel *et al.* 1987). Kromekote cards were also used to determine the volume of spray recovered at ground level for the two *B.t.* formulations by removing, concentrating and quantifying the dye. The quantity of dye was determined spectrophotometrically. The deposits on glass plates were quantified for the diflubenzuron formulation as described by Sundaram *et al.* (1987). The deposit data for the two applications of the *B.t.* formulations differed very little and were averaged for the two applications.

RESULTS AND DISCUSSION

Formulation Parameters

The viscosity of liquids is inversely related to the tendency of liquids to atomize into small droplets. Spray formulations are atomized at high shear rates. Therefore the viscosity shear-rate relationship can give an indication of expected droplet size.

The viscosity of the diflubenzuron formulation was low and changed only slightly with increasing shear rate (Fig. 1). Therefore this formulation had Newtonian characteristics. Such liquids break up easily and tend to have a wide droplet size spectrum. The viscosity of Futura XLV and Thuricide 48LV decreased rapidly with increasing shear-rate (Fig. 1). These formulations exhibited pseudoplastic behaviour, and these tended to break up into a narrow range of droplet sizes.

Increased surface tension increases the resistance to small droplet formation, and it also decreases evaporation of droplets in flight. The surface tensions of the three formulations were very similar near 40 mNm^{-1} (Fig. 2). Therefore surface tension would not contribute to differences in droplet size-spectra.

Diflubenzuron vaporized decidedly faster than did the two *B.t.* formulations; the latter were very similar to each other (Fig. 3). Diflubenzuron would have a smaller average droplet size when arriving at the canopy, because a higher proportion of the droplets would evaporate in flight.

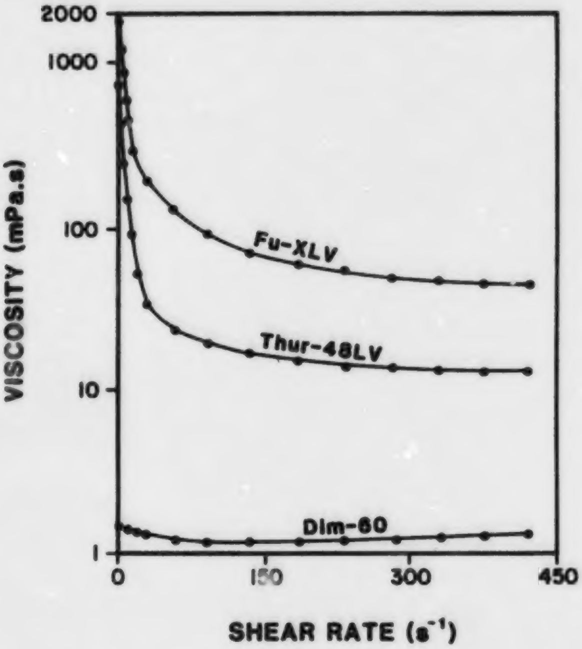

FIGURE 1: VISCOSITY SHEAR-RATE RELATIONSHIP OF SPRAY FORMULATIONS.

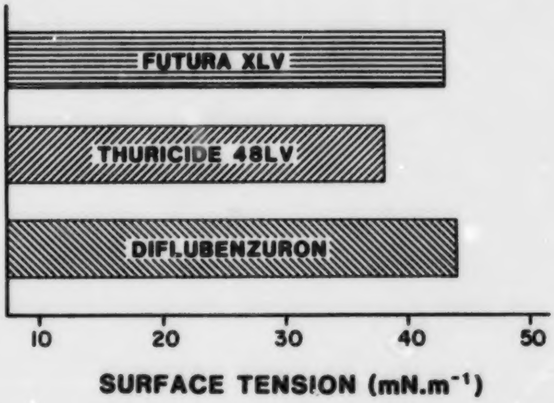

FIGURE 2: SURFACE TENSION OF SPRAY FORMULATIONS.

Droplet Spectra

Droplet spectra measured at ground level were in good agreement with formulation parameters. Diflubenzuron had a high proportion of small droplets (Fig. 4) and also the smallest Number Median Diameter (NMD) (Table 2); about half of those of the two *B.t.* formulations. The average small droplet size of the diflubenzuron formulation was probably caused by the low viscosity of the formulations and the faster rate of evaporation. However diflubenzuron also formed a few large droplets of 150-200 μm in diameter. These contained relatively large proportions of the spray volume arriving at ground level (Fig. 4). Although the presence of such large droplets is undesirable, the formulation is considered acceptable for ultra low-volume aerial application.

Futura XLV had a narrower droplet spectrum then did Thuricide 48LV (Fig. 4), and practically all of the spray volume arrived at the canopy in droplet sizes of less than 125 μm. Therefore Futura XLV forms a slightly better droplet spectrum than Thuricide 48LV, but both are acceptable for ultra-low volume aerial application.

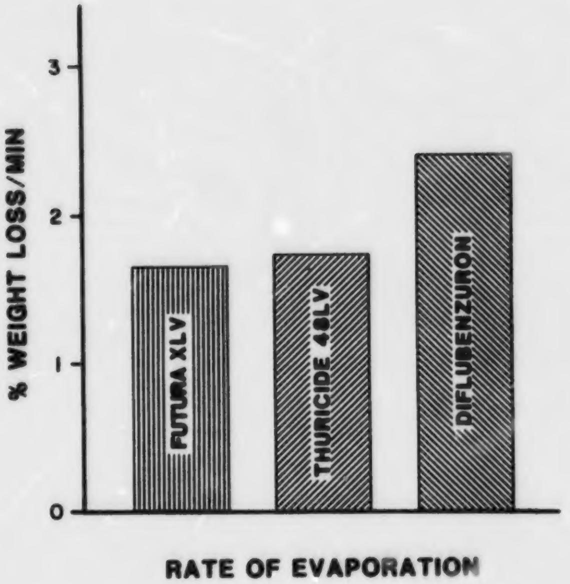

FIGURE 3A: EVAPORATION PARAMETERS OF FORMULATIONS: RATE OF EVAPORATION.

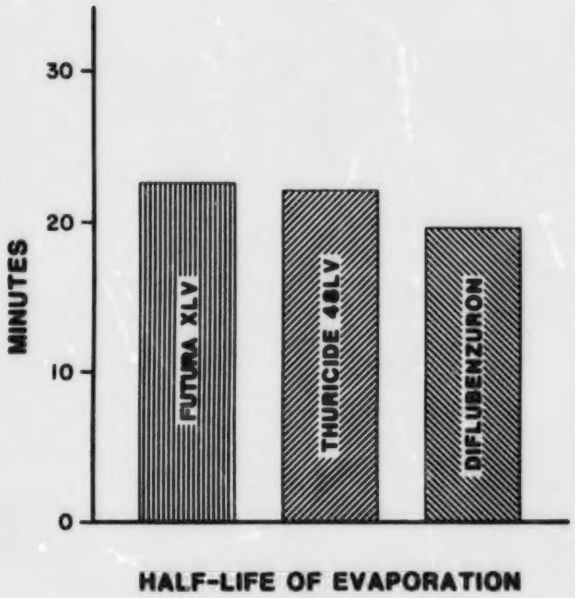

FIGURE 3B: EVAPORATION PARAMETERS OF FORMULATIONS: HALF-LIFE OF SPRAY DROPLETS.

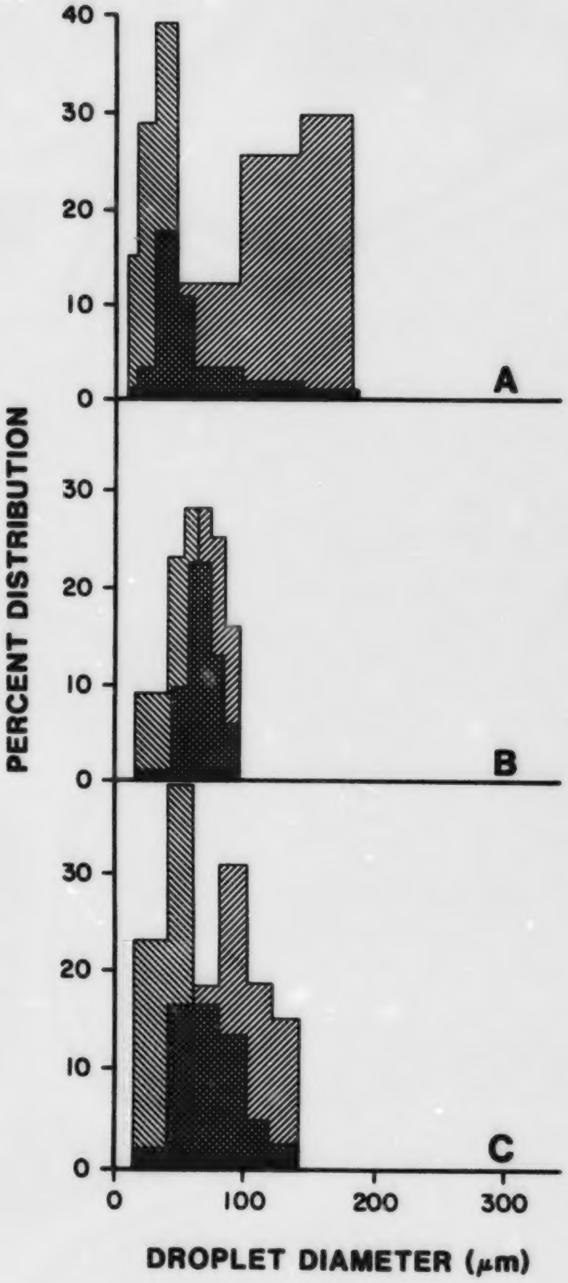

FIGURE 4: FREQUENCY DISTRIBUTION OF DROPLET NUMBER (LEFT PEAK) AND DROPLET VOLUME (RIGHT PEAK) OF FORMULATIONS OF (a) DIFLUBENZURON (b) FUTURA XLV, AND (c) THURICIDE 48LV.

TABLE 2: Droplet parameters of aerially applied formulations sampled near ground level (n = 21).

Parameter	Futura XLV	Thuricide 48LV	Diflubenzuron
Droplet Density (#/cm^2)	5.0	2.6	5.6
Max. diameter (μm)	90	138	182
Min. diameter (μm)	15	15	8
NMD (μm)	55	44	26
VMD (μm)	66	81	38
Volume deposited (mℓ/ha)	276	200	356
% Volume deposited on glass plates	13	8	18

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COMPARING ATOMIZATION CHARACTERISTICS AND DEPOSIT ON FOLIAGE OF SOME SUMITHION 20F AND MATACIL 180F FORMULATIONS

K.M.S. Sundaram[1], A. Sundaram[1], A.G. Raske[2], R.J. West[2], A. Retnakaran[1]

ABSTRACT — The viscosity of three Matacil 180F® formulations changed little as the shear rate increased, but the viscosity of two Sumithion 20F® formulations decreased rapidly. The Matacil 180F formulations had Newtonian characteristics, whereas the Sumithion 20F formulations exhibited pseudoplastic behaviour. The Sumithion 20F formulations had greater surface tension at 45 to 50 mNm^{-1} compared to that of the Matacil 180F formulations at 30 to 33 mNm^{-1}. The volatility of all formulations was similar with half lives of 10 to 13 minutes except for Sumithion 20F applied at 210 g ai/ha which had a half life of 27 minutes. The non-volatile component of the two Sumithion 20F formulations was low at 15% and 21%, but that of Matacil 180F steadily increased with increasing concentration from 35% at 90 g ai/ha to 70% at 180 g ai/ha.

Droplet size-spectra at ground level in field tests were similar to expectations from formulation parameters measured in the laboratory. Average droplet diameters of Matacil 180F formulations were smaller than those of Sumithion 20F. Foliage deposits of the pseudoplastic Sumithion 20F formulations were six to eight times greater than those of the Newtonian Matacil 180F formulations. Thus the advantage of polymeric ingredients, which caused pseudoplastic behaviour in insecticide formulations, was reflected in increased foliar deposit.

RÉSUMÉ — L'augmentation du taux de cisaillement modifiait peu la viscosité de trois préparations de Matacil 180F® contrairement à celle de deux préparations de Sumithion 20F® qui diminuait rapidement. Les préparations de Matacil 180F avaient des caractéristiques newtoniennes et celles de Sumithion 20F présentaient un comportement pseudoplastique. La tension de surface des deux préparations de Sumithion 20F était plus élevée à 45 à 50 mNm^{-1} que celle de la préparation de Matacil 180F à 30 à 33 mNm^{-1}. La volatilité de toutes les préparations était similaire, avec des périodes effectives de 10 à 13 minutes, sauf dans le cas de Sumithion 20F, qui atteignait 27 minutes lorsqu'appliqué à des doses de 210 g/ha d'ingrédient actif. La composante non volatile des deux préparations de Sumithion était faible à 15 et 21%, mais celle du Matacil 180F augmentait régulièrement avec l'accroissement des concentrations, allant de 35% à 90 g/ha d'ingrédient actif à 70% à 180 g/ha.

Lors d'essais sur le terrain, les spectres de grosseur des gouttelettes étaient similaires aux prévisions formulées à partir des paramètres des préparations mesurés en laboratoire. Le diamètre moyen des gouttelettes de Matacil 180F était inférieur à celui des gouttelettes de Sumithion 20F. Le nombre de gouttelettes des préparations pseudoplastiques de Sumithion 20F se déposant sur le feuillage était six à huit fois plus élevé que celles des préparations newtoniennes de Matacil 180F. Par conséquent, les avantages des ingrédients polymérisés, qui donnent aux préparations d'insecticides un comportement pseudoplastique, se concrétisent par une augmentation du nombre de gouttelettes se déposant sur le feuillage.

INTRODUCTION

Physical properties of insecticide formulations, such as viscosity, volatility and surface tension influence their atomization and deposition characteristics. The proportion of droplets in various size classes, the droplet size-spectrum, affects the number of droplets and the spray volume that impinge upon conifer needles in a forest spray operation (Himel and Moore 1969; Barry and Ekblad 1978; Himel *et al.* 1987). For spraying under favourable weather conditions of low wind speeds and temperature inversion, a high proportion of droplets of 70 µm to 100 µm diameter is desirable as these have a high probability of impinging on needles (Joyce and Beaumont 1978). Initial levels of insecticide deposit is usually measured on needles on one-year-old shoots (Sundaram *et al.* 1987b; Sundaram and Nott 1985).

We studied the relationship between some physical properties of two formulations of Sumithion 20F® (= fenitrothion) and three formulations of Matacil 180F® (= aminocarb) and their droplet size-spectra measured at ground level, after aerial applications. The amount of pesticide that impinged upon balsam fir [*Abies balsamea* (L.) Mill.)] needles from these applications were measured on one-year-old needles and on needles on the current shoot. The latter was measured because needles on current shoots are the primary food source of major defoliators such as the spruce budworm [*Choristoneura fumiferana* (Clem.)] and the eastern hemlock looper [*Lambdina fiscellaria fiscellaria* (Guen.)].

MATERIALS AND METHODS

All insecticides (Table 1) were aqueous formulations with the dye Erio Acid Red XB 400 (Keystone Aniline Co.) added at a concentration of 1% and the emulsifier Atlox 3409F was added at 1.5% concentration to Matacil 180F formulations. Sumithion

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[1] Canadian Forestry Service, Forest Pest Management Institute, Sault Ste. Marie, Ontario

[2] Canadian Forestry Service, Newfoundland Forestry Centre, St. John's, Newfoundland

20F formulations have polymeric ingredients, that tend towards pseudoplastic behaviour in the formulations, absent in Matacil 180F.

TABLE 1: Dosages, rates of application and weather parameters during aerial application of formulations in Newfoundland in 1985.

Parameter	Sumithion 20F		Matacil 180F		
Dose (g ai/ha)	140	210	90	135	180
Vol. rate (ℓ/ha)	1.5	1.5	1.5	1.5	1.5
Temp. (°C)	17	14	17	15	18
Rel. Hum. (%)	85	88	85	88	72
Wind speed (km/h)	2-6	3-7	1-6	4-7	5-6

Standard procedures were used to measure viscosity shear-rates and surface tension (Sundaram *et al.* 1987a; Glasstone 1946; Sundaram and Leung 1986). Volatility was determined by a gravimetric method (Sundaram and Leung 1986) and expressed as the time for half of the volatile droplet component to evaporate ($T_{1/2}$).

A Piper Pawnee aircraft equipped with six Micronair AU5000 atomizers was used to spray the formulations on 15 ha plots in 1985 in Newfoundland. The blade angle of the Micronairs was set at 35°. Air speed was 160 km/h and a 40 m swath width was used for spray volume calculations.

Spray deposit was measured with 10 cm × 10 cm Kromekote® cards and two glass plates, each 7.5 cm × 5.0 cm, placed about 30 cm above the ground at 15 m intervals across the plot (n = 21) before spray time. These cards were collected within 60 minutes after the spray. Cards were analyzed for droplet density, droplet diameter, and droplet volume (Sundaram *et al.* 1985).

Spray deposits on glass plates were eluted with methanol. The extracts were filtered, then flash evaporated and the residue taken up in a known volume of ethyl acetate. The active ingredients were determined by gas-liquid chromatography (Szeto and Sundaram 1980; Sundaram and Sundaram 1987). The detection limit of these techniques was 0.01 μg/ml.

Canopy foliage was sampled within one hour of the spray. Foliage from one mid-crown branch, cut from each of 11 trees at 30 m intervals, was used to determine spray deposit on foliage. The amount of active ingredient (ai) on current-year's shoots and on one-year-old needles was determined by gas-liquid chromotography (Szeto and Sundaram 1980; Sundaram and Sundaram 1987).

RESULTS AND DISCUSSION

Formulation Parameters

The tendency of liquids to atomize into small droplets is inversely related to the viscosity of the liquid. Therefore, the droplet-size expected can be indicated by the viscosity shear-rate relationship (Yates and Akesson 1973). The viscosity of the Sumithion 20F formulations decreased rapidly with increasing shear rates (Fig. 1). Therefore the formulation is pseudoplastic in

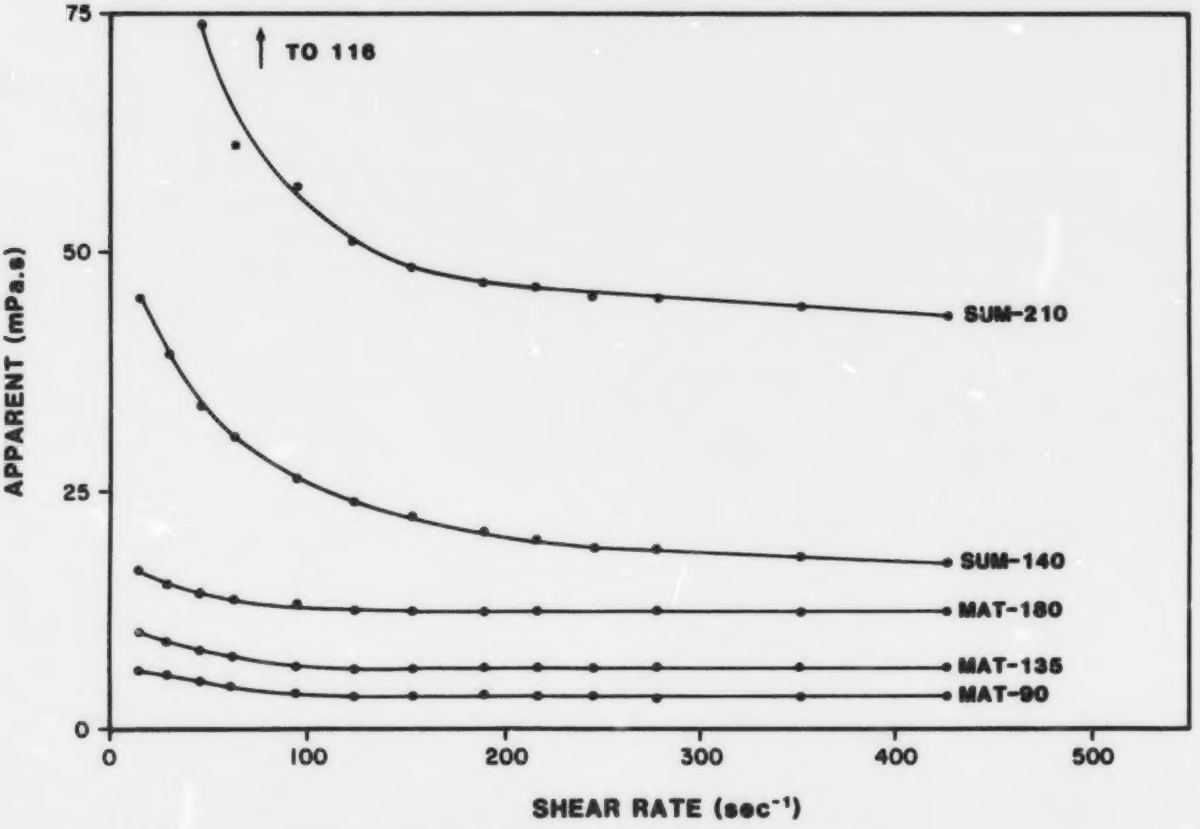

FIGURE 1: VISCOSITY SHEAR-RATE RELATIONSHIP OF MATACIL 180F AND SUMITHION 20F FORMULATIONS.

behaviour and would resist breaking up into extremely fine droplets (Sundaram and Retnakaran, 1987).

The viscosity of the Matacil 180F formulations changed very little as the shear rate increased (Fig. 1). These formulations had Newtonian characteristics and tended to break up easily into small and large droplets (Sundaram 1987) yielding a wide droplet spectrum.

Increased surface tension usually increases resistance to formation of small droplets and also decreases evaporation of droplets in flight (Yates and Akesson 1973; Matthews 1979). The surface tension of the two Sumithion 20F formulations measured were decidedly higher than those of Matacil 180F (Fig. 2). Therefore, Matacil 180F should form a larger proportion of small droplets if other characteristics are equal.

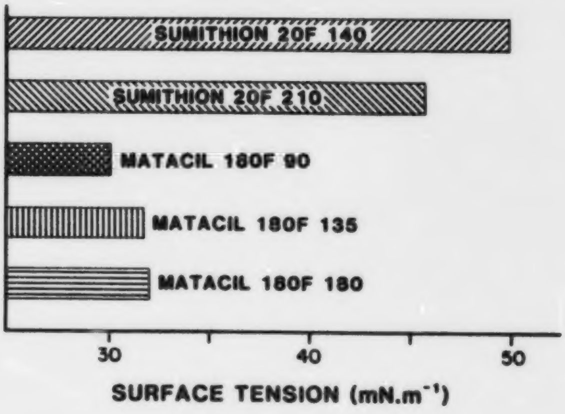

FIGURE 2: SURFACE TENSION OF SPRAY FORMULATIONS.

The volatility of the spray formulations ($T^{1/2}$) was similar for all formulations except for Sumithion 20F at 210, which evaporated more slowly (Fig. 3). However, the non-volatile component of the formulation (Fig. 4) also affects volatility. Volatility decreases with an increase in the non-volatile component. Therefore, volatility of Matacil 180F should be lower than that of Sumithion 20F because of the higher percent of the non-volatile component (Figs. 3, 4) of Matacil 180F. However, the rate of evaporation was much higher for Matacil 180F formulations than for Sumithion 20F. All else being equal Matacil 180F should reach the target in smaller droplets than Sumithion 20F. Among the three Matacil 180F formulations, and among the two Sumithion 20F formulations, volatility decreased with increasing concentration of the active ingredient.

Droplet Spectra

Droplet size-spectra at ground level in field tests were similar to expectations from formulation parameters measured in the laboratory. Average diameter of droplets reaching the ground was smaller for the Matacil 180F formulations than for the corresponding Sumithion 20F formulations (Table 2, Fig. 5). This was true for all droplet parameters.

Among the three Matacil 180F and the two Sumithion 20F formulations measures of average droplet size increased with increasing concentration of the active ingredient (Table 2).

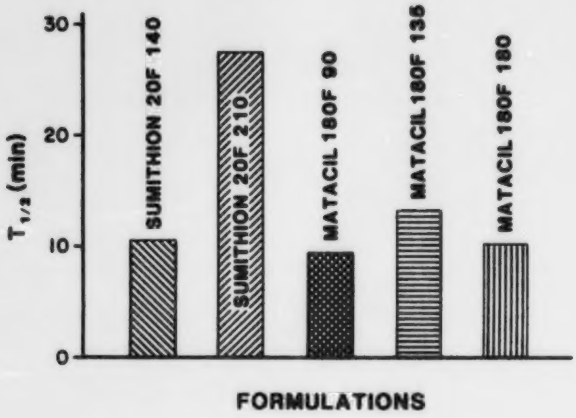

FIGURE 3: VOLATILITY OF SPRAY FORMULATIONS IN HALF-LIFE OF VOLATILE COMPONENT.

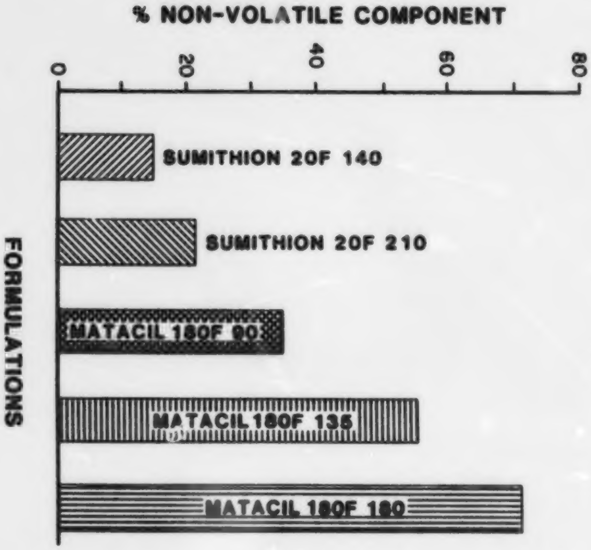

FIGURE 4: PERCENT NON-VOLATILE COMPONENT OF SPRAY FORMULATIONS.

TABLE 2: Droplet parameters of aerially applied formulations sampled near ground level (n = 21).

Parameter	Sumithion 20F		Matacil 180F		
Dosage (g ai/ha)	140	210	90	135	180
Droplet density	15.7	7.6	9.4	8.9	4.3
Max. diameter	126	215	70	90	120
Min. diameter	8	9	5	5	5
NMD	26	88	11	17	57
VMD	63	133	48	57	66
Vol. deposited (g ai/ha)	22.1	37.8	7.7	8.7	15.3
% ai deposited on glass plates	15.8	18.0	8.6	6.5	8.5

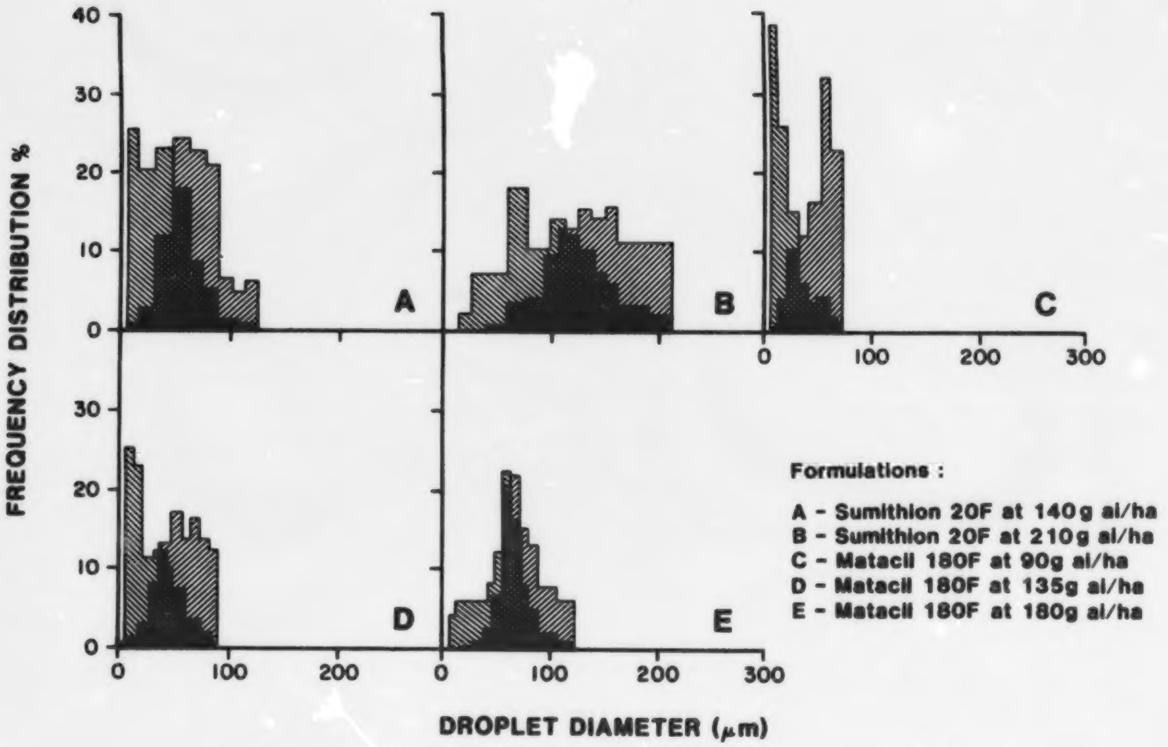

FIGURE 5: FREQUENCY DISTRIBUTION OF DROPLET NUMBER (LEFT PEAK) AND DROPLET VOLUME (RIGHT PEAK) OF FORMULATIONS.

The volume of the active ingredient deposited near the forest floor was higher for Sumithion 20F than for Matacil 180F in both absolute and in relative measures (Table 2). The proportion of Sumithion 20F reaching the ground was usually twice as large as the proportion of Matacil 180F deposited.

The relationship of formulation parameters to droplet spectra in Sumithion 20F is not directly comparable to that in Matacil 180F because Sumithion 20F contains polymeric ingredients which impart pseudoplastic properties. These properties caused higher deposits at ground level for Sumithion 20F formulations.

Generally, Matacil 180F formulations had a higher proportion of droplets in the undesirable size range of extremely fine droplets of less than 50 µm (Fig. 5) and a smaller proportion of spray volume reached the ground in optimum droplet size of 70 µm to 100 µm than for the Sumithion 20F formulations.

Foliage Deposit

Droplets of Sumithion 20F on foliage were six to eight times greater than those of Matacil 180F (Fig. 6), a result unexpected from deposit data at ground level. The pseudoplastic behavior of Sumithion 20F formulations and the absence of extremely fine droplets in the spray cloud probably caused these large foliar deposits.

The average amount of deposit on foliage within Sumithion 20F and Matacil 180F always increased with increasing concentration of the formulation, but the differences were not statistically significant ($P \leq 0.05$). Similarly, deposit on current growth was always greater than on one-year-old growth, but the trend was statistically significant only for both the Sumithion 20F treatments ($P \leq 0.05$).

The influence of viscosity and volatility on foliar deposits among formulations of Sumithion 20F and Matacil 180F tested appears slight. However, the differences between foliar deposits of Sumithion 20F and deposits of Matacil 180F was large and reflected the presence of polymeric ingredients in Sumithion 20F. The advantage of pseudoplastic behavior of insecticide formulation, such as Sumithion 20F, tends to result in good foliage deposit.

ACKNOWLEDGEMENTS

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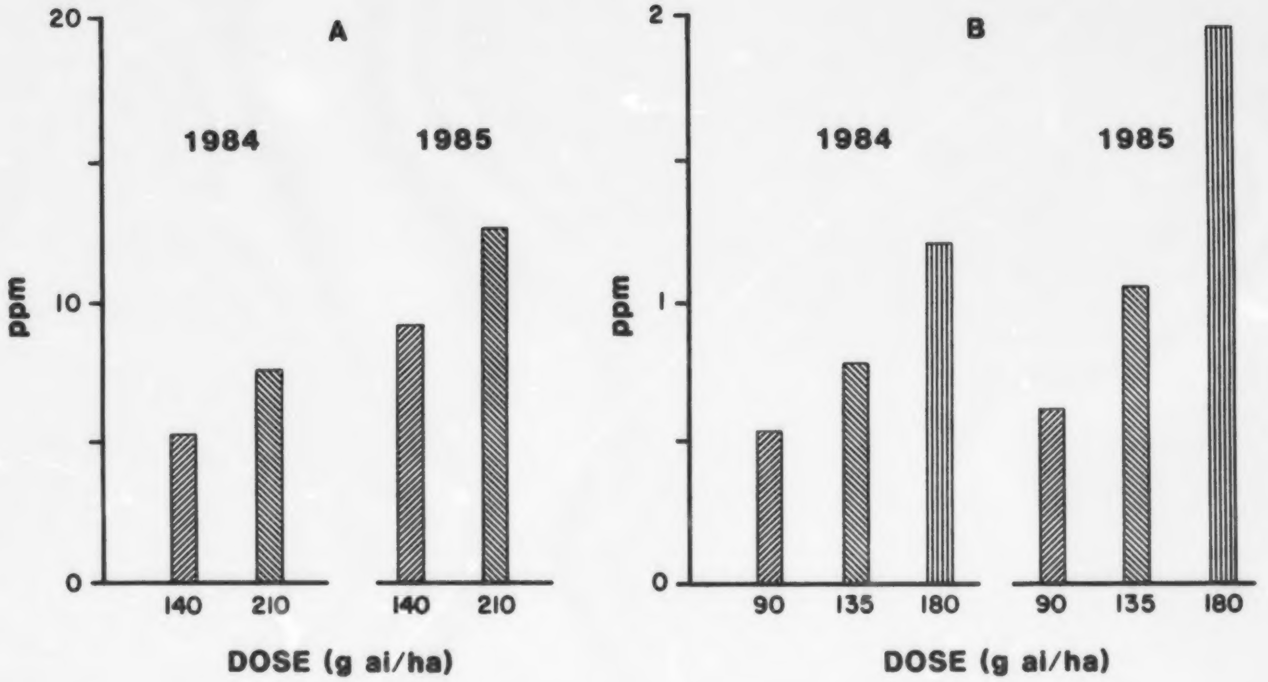

FIGURE 6: VOLUME OF SPRAY IN PPM ON CURRENT AND ONE-YEAR-OLD BALSAM FIR FOLIAGE.
A. SUMITHION 20F; B. MATACIL 180F.

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DROPLET SIZE SPECTRUM AND DEPOSIT PATTERN OF THURICIDE® 48LV SPRAYED AERIALLY OVER A SPRUCE PLANTATION IN ONTARIO

A. Sundaram[1], K. van Frankenhuyzen[1], J.H. Meating[2], and G.M. Howse[2]

ABSTRACT — Atomization characteristics, droplet size spectrum and deposit pattern of a commercial *Bacillus thuringiensis* formulation, Thuricide® 48LV, were studied following aerial application in a 60-ha white spruce plantation in northern Ontario. Spray was applied undiluted at 30 BIU in 2.4 L/ha using a Bell 206 helicopter fitted with four Micronair® AU5000 atomizers. Spray deposits were sampled at ground level using Kromekote® cards and glass plates. Foliar droplets were counted on trees in the vicinity of the ground sampling units. The formulation had optimum physical properties and atomized uniformly, producing a narrow droplet size spectrum on the sampling cards. Droplet distribution was also uniform, with a high number of 85 droplets per cm^2 on the cards. Spectrophotometric analysis of deposits on glass plates indicated an average spray recovery of about 90% at ground level. Foliar deposits ranged from 0 to 7 droplets per needle, with a mean of 2.5 droplets per needle. Our deposit and recovery estimates are among the highest values reported in the literature to date.

RÉSUMÉ — Les caractéristiques d'atomisation, le spectre de taille des gouttelette et le mode de dépôt d'une préparation commerciale de *Bacillus thuringiensis*, le Thuricide^{md} 48LV, ont été étudiés à la suite du traitement par voie aérienne d'une plantation d'épinettes blanches, dans le nord de l'Ontario. La pulvérisation a été effectuée sans dilution à raison de 30 UBI dans 2,4 L/ha au moyen d'un hélicoptère Bell 206 équipé de quatre pulvérisateurs Micronair^{md} AU5000. Les dépôts ont été échantillonnés au niveau du sol à l'aide de cartes Kromekote^{md} et de plaques de verre. On a compté les gouttelettes déposées sur les aiguilles des arbres situés dans le voisinage des unités d'échantillonnage au sol. La préparation présentait des propriétés physiques optimales et avait été pulvérisée de façon uniforme, produisant un étroit spectre de taille des gouttelettes sur les cartes d'échantillonnage. La répartition des gouttelettes était également uniforme et un nombre élevé de gouttelettes, 85/cm^2, a été observé sur les cartes. L'analyse spectrophotométrique des dépôts recueillis sur les plaques de verre indiquait un taux de récupération moyen du produit pulvérisé d'environ 90 % au niveau du sol. Les dépôts foliaires variaient de 0 à 7 gouttelettes par aiguille, la moyenne étant de 2,5 gouttelettes par aiguille. Nos estimations du dépôt et du taux de récupération comptent parmi les plus élevées signalées dans la documentation jusqu'à maintenant.

INTRODUCTION

In forestry applications of pesticides, atomization of the spray formulation and spray deposition depend on physical properties of the formulation, the type of atomizer used, dispersal parameters (Randall, 1977; Bode et al., 1982; Yates, 1985; Sundaram, 1987), spray release height (Joyce and Spillman, 1978), tree canopy height, tree density (Jackson, 1981) and meteorological conditions (Yates and Akesson, 1973; Armstrong, 1977).

Observations on spray deposition under a variety of conditions are useful to characterize what can be reasonably expected to result from an aerial application. West et al. (1987) reported data on spray deposition on Kromekote® cards and foliage measured in a mature forest after application of Thuricide® 48LV. The formulation was applied undiluted at 30 BIU/ha in 2.4L by a fixed wing aircraft equipped with six Micronair® AU5000 atomizers. Their data indicated low spray deposition at canopy and ground level. In this paper we present contrasting observations on spray deposition of the same formulation in a young plantation. Thuricide 48LV was applied undiluted at 30 BIU/ha in 2.4L by a Bell 206 helicopter equipped with four Micronair AU5000 atomizers. We measured spray deposition at ground level and in the tree canopy and related observed atomization characteristics to physical properties of the formulation.

EXPERIMENTAL METHODS

Experimental Plot

A 60-ha white spruce [*Picea glauca* (Moench) Voss] plantation was selected in Marks Township 16 km west of Kakabeka falls in northwestern Ontario. The plantation contained small trees (about 1.8 m high) planted at 3 m intervals in a 200 m wide strip through the middle portion of the spray plot, surrounded by 9 to 10 m high trees. The plantation was successfully treated against budworm defoliation in previous years and the trees were generally in good shape.

Spray Application and Meteorological Conditions

A water-soluble fluorescent dye was added at 0.2 g/100 mL to the commercial formulation to facilitate deposit assessment. A Bell 206 helicopter fitted with four Micronair AU5000 atomizers applied the spray along a direction at right angles to the sampling line A (Fig. 1). Application details and meteorological conditions during treatment, are given in Table 1.

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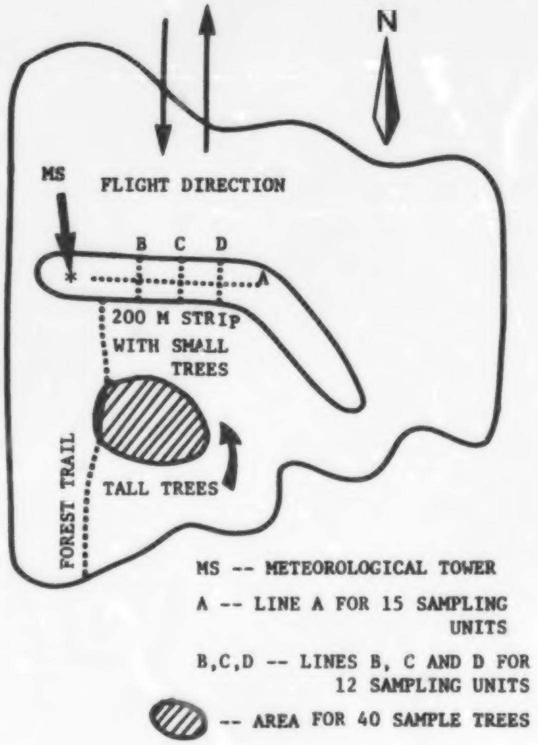
N
FLIGHT DIRECTION
MS
B C D
A
200 M STRIP WITH SMALL TREES
TALL TREES
FOREST TRAIL
MS -- METEOROLOGICAL TOWER
A -- LINE A FOR 15 SAMPLING UNITS
B,C,D -- LINES B, C AND D FOR 12 SAMPLING UNITS
▨ -- AREA FOR 40 SAMPLE TREES

FIGURE 1: SPRAY PLOT LAYOUT AND LOCATION OF GROUND SAMPLING UNITS AND SAMPLE TREES.

Foliar Droplet Assessment

One branch was clipped from the upper part of the tree crown in each sample tree 2 h after application. Five twigs were collected from each branch, one shoot was clipped from each twig, and 10 flushed needles were collected from each shoot. This sampling regime provided a sample of 50 needles from each tree (Fig. 2), or 2000 needles from the 40 sample trees. Each spruce needle was mounted with one end into the capillary portion of a disposable Pasteur pipette (Fig. 3), which in turn was placed on a groove made in a rubber slab, to facilitate easy rotation of the pipette for droplet counting on all sides of the needle. Because the relative humidity was high (97%) during spray application, there was a heavy dew on the foliage. As a result, droplets underwent complete spreading forming irregularly-shaped stains on foliage, and this made droplet sizing difficult. However, droplets could be counted to provide data on droplets per needle (Table 1). Drop density ranged from 0 to 7 droplet/needle with a mean of 2.5 (Fig. 4).

Spray Deposit Assessment at Ground Level

The conventional Kromekote card/glass plate units (Randall, 1980) were used for assessing ground deposits. Fifteen units were laid out in the vicinity of the small trees at 10 m intervals along line A in Fig. 1, and four along each of the lines B, C and D, perpendicular to line A. A total of 27 units were used. They were laid out 0.5 h before spray application and collected 1.0 h after spraying.

TABLE 1: Spray application details and meteorological factors; and physical properties, droplet size spectrum, ground deposit and foliar droplet data during a helicopter application of Thuricide® 48LV in Ontario

Spray plot size:	60 ha
Date of application:	June 6, 1986
Time of application:	0640
Temperature (mean):	3.5°C
Wind speed:	Still air
Relative humidity:	97%
Precipitation:	Nil
Aircraft type:	Bell 206 helicopter
Aircraft speed:	120 km/h
Spray height:	15 m above canopy
Atomizer units:	4 × Micronair® AU5000
Atomizer blade angle:	35°
Swath width:	45 m
Emission rate:	22 L/min
Dosage rate:	30 BIU/ha
Volume rate:	2.4 L/ha
No. of sample trees used:	40
No. of ground samplers:	27
Physical properties:	
Viscosity (mPa·s)[a]	40.5
Surface tension (mN/m)	34.1
Volatility data[b]	
a. Non-vol. (%)[c]	85 w/w
b. R (Evap) (%)[d]	0.8
Droplet size spectrum:	
D_{min} (μm)	15
D_{max} (μm)	140
$D_{N.5}$ (μm)	42
$D_{V.5}$ (μm)	78
Droplets/cm² (mean ± SD)[f]	85 ± 18
Ground deposit data:	
Spray vol. recovery[f]	2.11 ± 0.38 L/ha
Percent recovery[f]	88 ± 16
Foliar droplet data:	
No. per needle (mean ± SD)[g]	2.5 ± 1.2

[a]: Viscosity at a shear rate of 280 s^{-1} is reported here.

[b]: Volatility was determined by a gravimetric method (Sundaram and Leung, 1986).

[c]: Non-vol (%) = the percent residual weight that did not show any detectable evaporation for 120 h.

[d]: R (Evap) = rate of evaporation, i.e., the decrease of residual weight (%) per minute.

[f]: Mean ± SD values were obtained from the total number of samplers used in the spray area.

[g]: Mean ± SD values were obtained from the tree mean values calculated from the 40 trees used in the spray plot.

Microscopic analysis of the Kromekote cards indicated that over 90% of the droplets that impinged on the card were completely spherical and were below 80 μm in diameter. The minimum diameter (D_{min}) was 15 μm (Table 1). Spherical droplets showed good adhesion to the card since droplets could not be removed by mechanical means. Of the remaining droplets, about 9% were in the 80 to 110 μm range and only 1% was between 110 and 140 μm, the D_{max}. Droplets from 80 to 110 μm were hemispheres (with a spread factor of 1.25) and larger droplets were completely spread (with a spread factor of 1.7). The spherical diameters of these droplets were calculated using the spread factor data. Droplet size spectra were evaluated according to Johnstone (1978). The

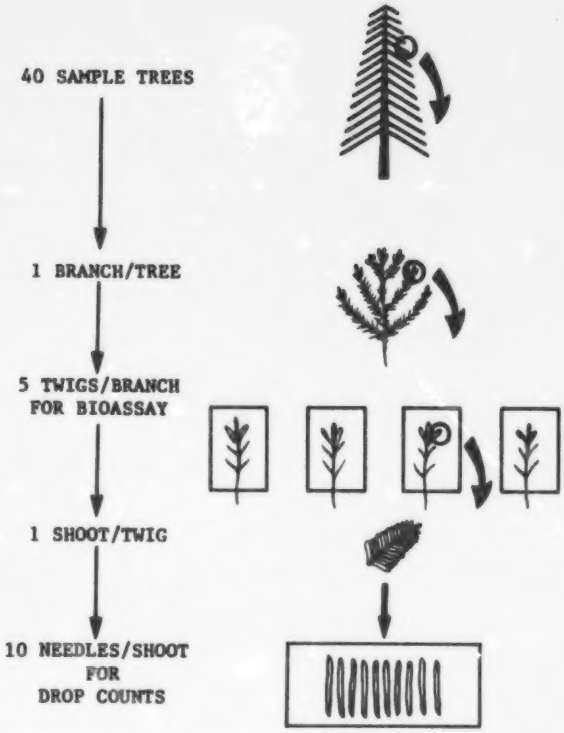

FIGURE 2: SAMPLING REGIME FOR FOLIAR DROPLET ASSESSMENT.

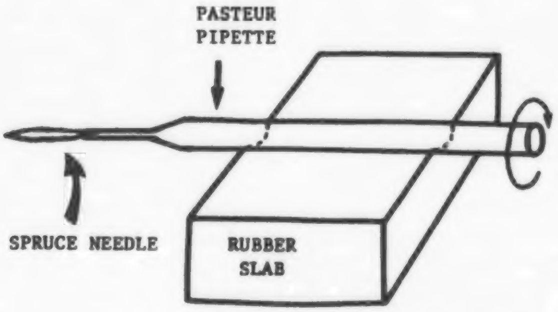

FIGURE 3: MOUNTING OF A SPRUCE NEEDLE IN A PASTEUR PIPETTE FOR DROPLET COUNTING.

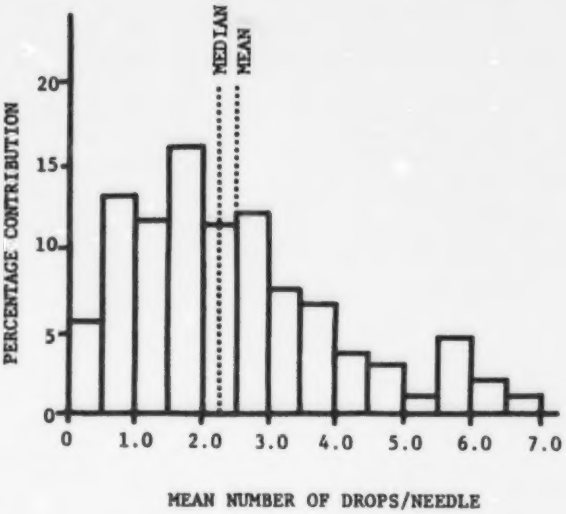

FIGURE 4: FREQUENCY DISTRIBUTION OF DROPLET DENSITY ON WHITE SPRUCE NEEDLES.

data obtained from each card were grouped in diameter classes and the number and volume median diameters ($D_{N.5}$ and $D_{V.5}$ respectively) and the number of droplets per cm^2 were computed. Data from the 27 cards were used to calculate the mean and standard deviations for the treatment (Table 1), and to compute frequency and volume distribution percentages (Fig. 5). The number of droplets per cm^2 obtained from the individual cards placed along each of the lines A, B, C and D were plotted against distance, in order to examine the spray distribution pattern over the area sampled (Fig. 6).

The droplets deposited on glass plates were eluted using methanol as the solvent for extracting the tracer dye added to the formulation. The eluate from each glass plate was filtered, centrifuged to remove the particulate impurities and concentrated to a known volume. The amount of dye present in the extract was quantified using a Beckman DU-7 Spectrophotometer (Beckman Instruments, Inc., Palo Alto. California, USA), and the volume of spray recovered on each glass plate unit (2 glass plates, each 7.5 cm × 5.0 cm) was computed along with the percent recovery. The data obtained from the 27 glass plate units were then used to calculate the mean and standard deviations (Table 1). The percent recovery obtained from the individual glass plate units placed along each of the lines A, B, C and D were plotted against distance, in order to examine the spray deposit pattern over the area sampled and the extent of swath overlap along the sampling line A (Fig. 7).

Physical Properties of the Formulation

Physical properties measured were: viscosity at variable shear rates, surface tension and volatility. These were measured in the laboratory either in an environmental chamber or in a thermostatic bath, maintained at the same temperature as encountered in the field. The properties were measured as described by Sundaram et al. (1987), and the relevant parameters are given in Table 1 and Fig. 8.

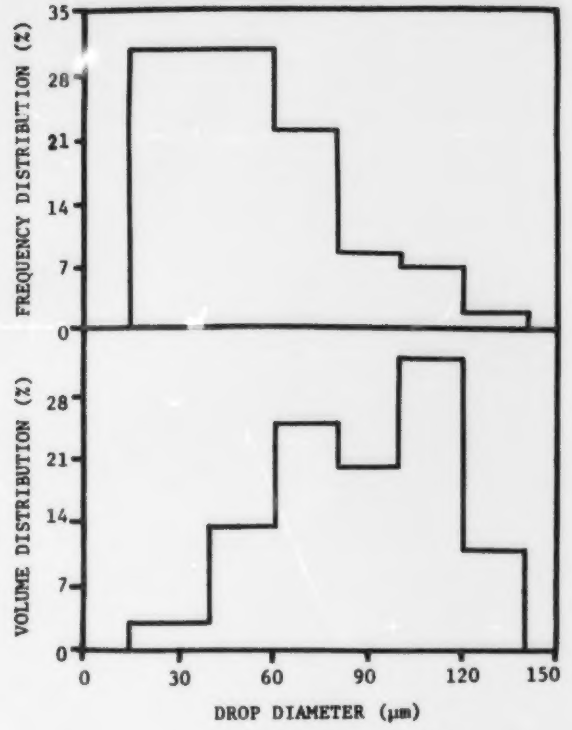

FIGURE 5: DROPLET FREQUENCY AND VOLUME DISTRIBUTION PERCENTAGES ACCORDING TO SIZE CATEGORY OF THURICIDE 48LV FORMULATION, AFTER HELICOPTER SPRAYING.

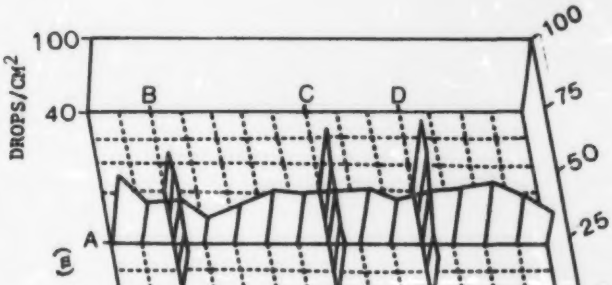

FIGURE 6: DROPLET DISTRIBUTION PATTERN ALONG THE SAMPLING LINES A, B, C AND D, AT GROUND LEVEL.

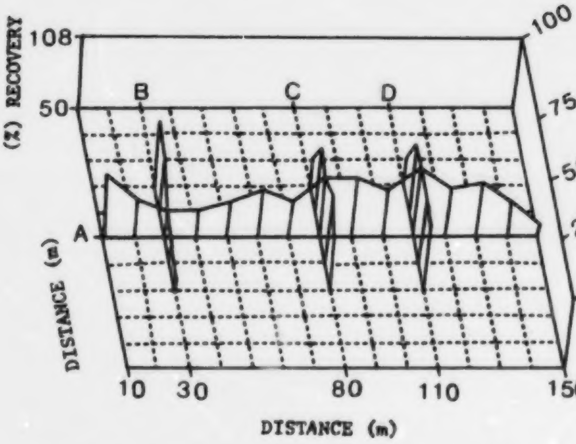

FIGURE 7: PERCENT RECOVERY OF SPRAY VOLUME DEPOSIT ALONG THE SAMPLING LINES A, B, C AND D, AT GROUND LEVEL.

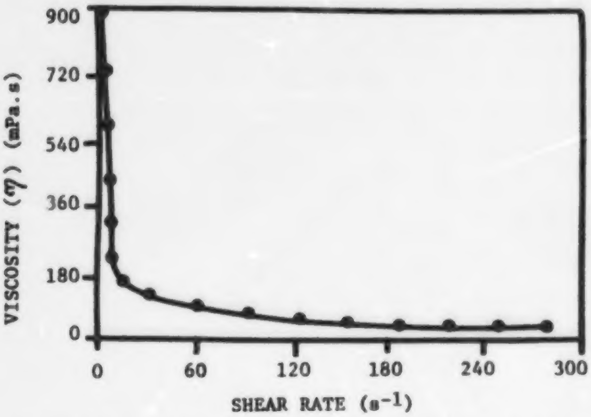

FIGURE 8: VISCOSITY-SHEAR RATE RELATIONSHIP OF THURICIDE 48LV FORMULATION.

DISCUSSION

Droplet size spectra on Kromekote cards provide useful information on the atomization of a formulation in ULV applications (Sundaram and Retnakaran, 1987). Kromekote cards placed horizontally at ground level selectively sample the upper part of the drop size spectrum, because only larger droplets have the required energy to impact on the flat sampling cards. Since large droplets (i.e., those 250 µm in diameter) are undesirable in ULV applications, their absence on Kromekote cards indicate efficient atomization of the spray formulation. Therefore, the $D_{N.5}$ and $D_{V.5}$ values of the drop size spectrum observed on flat ground samplers provide information on atomization efficiency, especially at high humidity when in-flight evaporation of droplets is minimal. In the present study, about 90% of the droplets that impinged on the sampling cards were below 100 µm in diameter (Fig. 5). The droplet volume distribution indicate that about 90% of the spray volume that deposited on the cards was below 120 µm, indicating a narrow droplet size spectrum. Thus the size spectrum and volume distribution suggest a high atomization efficiency of the Thuricide 48LV formulation in the delivery system used.

Uniform atomization of the formulation is attributable to optimum physical properties, in particular viscosity and surface tension. Volatility affects in-flight evaporation of droplets in ULV applications, but played a minimal role in this study because of the high humidity conditions and a low rate of evaporation (Table 1). The viscosity-shear rate relationship (Fig. 8) shows a rapid decrease of the initial high viscosity (of about 900 mPa·s) as the shear rate increased, indicating a pseudoplastic behavior. However the curve levelled off beyond a shear rate of 120 s^{-1}, indicating moderate pseudoplasticity. Moderately pseudoplastic liquids atomize into a narrow drop size spectrum (Sundaram, 1987) and provide a high droplet density on targets. The low surface tension also contributed to the narrow droplet spectrum as it enhances the formation of small droplets (34.1 mN/m, as compared to that of water, 72.5 mN/m) (Sundaram et al., 1987).

Deposition of the emitted spray on both ground and canopy was excellent. The observed mean density of 85 drops/cm^2 on the cards and the estimated recovery of about 90% are much higher than values previously reported for forestry application (Cadogan et al. 1984, 1986; Sundaram et al. 1985; West et al. 1987). An average density of 2.5 droplets/needle is also considerably higher than foliar deposit[illegible]ported by West et al. (1987) and Himel et al. (1987). Spray deposition was highly uniform along the sample lines, both in drop density and spray recovery (Fig. 7). Moderate variation along line A, perpendicular to the flight direction, is attributable to overlap of adjacent swaths. High drop density, uniform deposit distribution and high recovery of the emitted volume are attributable to optimum physical properties of Thuricide 48LV resulting in a narrow droplet size spectrum, suitable weather conditions during application, low release height of the spray above the tree canopy, high vortex descent rate, and the open nature of the forest type. We feel that our observations represent a best-case scenario of the type of results one can expect from an ULV application in forestry.

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THE DRIFT AND DEPOSITION OF CHARGED DROPLETS ON TREE CANOPIES; THE DEVELOPMENT OF AN EXPERIMENTAL PROCEDURE USING THE BOUNDARY LAYER WIND TUNNEL

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ABSTRACT — This paper is concerned with the development of a research procedure for modelling the dispersion and measuring the deposition of charged droplets — usually pesticides — on simulated tree canopies in a Boundary Layer Wind Tunnel. The procedure involves charging of the droplets to known values of charge to mass ratios and measuring the electrical charges collected by trees in the model forest or orchard mounted in the Boundary Layer Wind Tunnel. From the values of the charge to mass ratios and electrical charges collected by the trees, one can calculate the mass deposit on the trees.

The described experimental procedure shows considerable promise for the evaluation of the effectiveness of various spraying techniques and in particular those involving electrostatic enhancement of the deposition. At very low charge to mass ratios, the electrostatic enhancement of the deposition could be made negligible and as such the procedure is also suitable for the evaluation of standard mechanical spraying. With more elaborate model trees, one could study the penetration of droplets within the canopy.

The procedure offers an economic alternative to full scale experimentation, and in particular for studies of drift. It is known that drift studies under full scale experimentation are subject to extreme variations due to unpredictable winds.

A further advantage of the procedure is the immediate feedback and/or continuous measurements. With existing chemical methods, there is considerable lag between the test and the availability of the results.

RÉSUMÉ – Cet article porte sur le mise au point d'une méthode de recherche permettant de modéliser la dispersion de gouttelettes chargées — habituellement des pesticides — sur des couverts forestiers simulés dans une soufflerie de ce genre et de mesurer les dimensions de ces gouttelettes. Cette méthode consiste à donner aux gouttelettes une charge électrique connue par rapport à leur masse et à mesurer la charge accumulée sur les arbres de la forêt ou du verger modèle construit dans cette soufflerie. Connaissant le rapport charge: masse des gouttelettes et la charge accumulée sur les arbres, on peut calculer la masse du liquide retombé sur les arbres.

Le mode expérimental décrit dans ce texte est fort prometteur pour l'évaluation de l'efficacité des diverses techniques d'épandage, surtout de celles où les retombées sont augmentées par l'application d'une charge électrostatique sur les gouttelettes. Il serait possible, en fixant un rapport charge: masse très faible, de rendre négligeable l'action électrostatique sur les retombées et, par conséquent, d'utiliser cette technique pour évaluer les systèmes mécaniques standard de pulvérisation. Une modélisation plus élaborée des arbres permettrait d'étudier la pénétration des gouttelettes dans le couvert forestier.

Cette technique serait un substitut rentable aux expériences en vraie grandeur, en particulier pour l'étude de la dérive des gouttelettes; en effet, il est notoire que celle-ci subit des variations extrêmes à cause de l'imprévisibilité des vents.

Cette technique a aussi l'avantage de rendre possible une rétroaction immédiate et/ou des mesures en continu. Dans le cas des méthodes chimiques actuelles, il s'écoule un laps de temps considérable entre les essais et l'obtention des résultats.

INTRODUCTION

The recent developments in electrostatic spraying (1, 2 and 3) in agriculture have been prompted primarily by the requirements to minimize the drift of insecticides to neighbouring fields. In turn, such developments brought to light the needs for better and faster evaluation methods of the drift and implicitly the effectiveness of deposition in target areas.

The new evaluation method, described in this paper, involves charging the droplets to known values of charge-to-mass ratios and measuring the electrical charges collected on chosen targets. From the charge-to-mass ratios of the sprayed liquids and the total electrical charge collected, one can calculate the mass deposit.

It is believed that the new method will supplement and in some case replace the existing physical and chemical methods such as water-sensitive papers, fluorescent dies, chemical tracers, etc. which require lengthy, post-experimental, analytical work.

The new method is suited for boundary layer wind tunnel modelling — where the wind speed, direction and turbulence characteristics can be controlled.

This overcomes many of the difficulties familiar to field experimenters encountered in the evaluation of a new sprayer under variable and unpredictable wind conditions.

Wind tunnel model simulations provide effective means for studying the action of wind on buildings and structures and various other wind engineering problems including atmospheric diffusion and transport of gaseous and particulate substances. The facilities at the Boundary Layer Wind Tunnel Laboratory are well established and have been used effectively to study various engineering problems in the atmospheric boundary layer (5, 6, 7).

THE APPARATUS

The apparatus used in the development of the new method for the use in the boundary layer wind tunnel of The University of Western Ontario involves:

I: a charging system for the water (insecticide) droplets to known and controllable charge-to-mass ratios.

II: miniature spray (charge) collectors simulating the trees or vegetation.

III: a computer-based data acquisition system for measuring the accumulating deposition on the model orchard and instantaneously displaying the results.

The experimental setup for charging the droplets is shown in Figure 1.

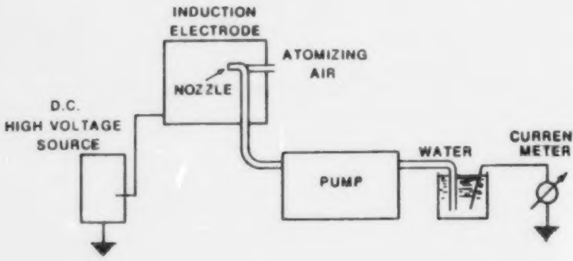

FIGURE 1: SCHEMATIC OF DROPLET CHARGING

Assuming positive polarity at the induction electrode, the atomized water will be charged negatively. The current (Ampere) divided by the waterflow, (gram/second) gives directly charge-to-mass ratio in Coulomb/gram. Figure 2 shows the charge-to-mass values obtained at various voltages applied to the induction electrode.

The model trees [7 cm in diameter, 5 cm high] were in the form of a metal cup mounted face down on electrically insulating (stems) supports. The stems contained a small, charge integrating circuit on a printed circuit board, see Figure 3.

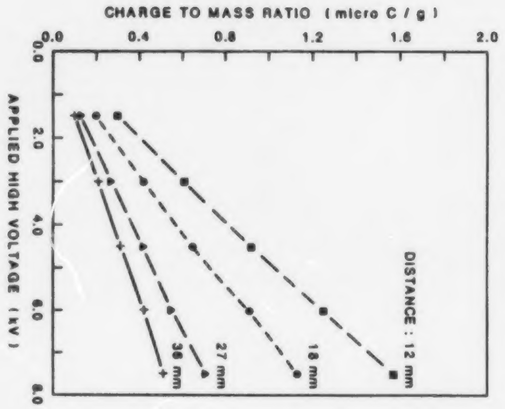

FIGURE 2: CHARGE TO MASS RATIO AT DIFFERENT DISTANCES FROM NOZZLE FOR VARIOUS CHARGE VOLTAGES

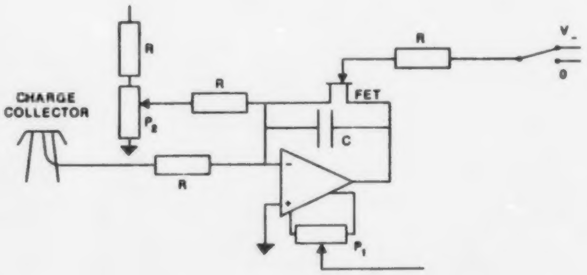

FIGURE 3: INTEGRATING CIRCUIT CONTAINED IN MODEL TREES

THE EXPERIMENTS

The experiments were carried out in one of the boundary layer wind tunnels at the Boundary Layer Wind Tunnel Laboratory of The University of Western Ontario. These wind tunnels are capable of reproducing the turbulence and mean wind characteristics of the natural wind over different types of terrain. The wind tunnel used had a working section 8 ft. (2.4m) wide and approximately 100 ft. (30m) long. A model "forest" of several hundred identical "trees" was constructed and arranged on the wind tunnel floor in rows parallel and perpendicular to its centreline, see Figure 4. A total of sixteen instrumented trees, positioned in the pattern shown in Figure 5, were used to measure the electrical charges deposited with the charged water spray.

The charged water spray was injected upwind in to the air stream at approximately 20 cm above the "tree" canopy at the location shown in Figure 5. Model trees (uninstrumented) also extended upstream of the nozzle position.

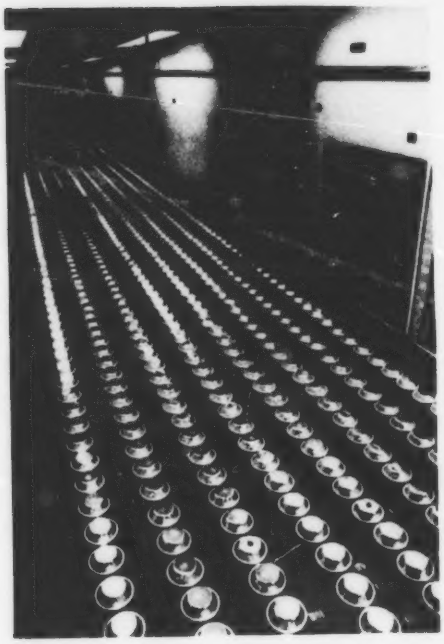

FIGURE 4: PHOTO OF MODEL FOREST IN WIND TUNNEL

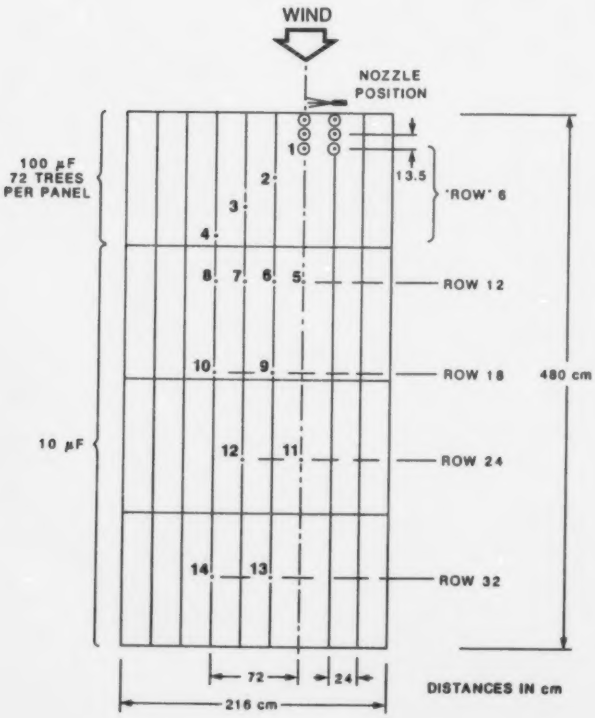

FIGURE 5: DOWNSTREAM PATTERN OF INSTRUMENTED TREES USED IN EXPERIMENT

The experiments were carried out at wind speeds in the wind tunnel of 1, 2 and 5 ft/second [0.3, 0.6 and 1.5 m/s] and at a low and high charge-to-mass ratio. Froude number scaling applies in these experiments. Correspondingly, the velocity scaling is proportional to the length scaling. Assuming the length scaling is roughly 25:1 implies that the velocity scaling is roughly 5:1. The test wind speeds would then correspond to roughly 1.5, 3 and 7.5 m/s in full scale. These are referred to as the 'Low', 'Medium' and 'High' wind speed results.

A high charge-to-mass ratio may be representative of an electrostatic spraying system whereas a low charge-to-mass ratio may simulate conditions of typical mechanical spraying.

RESULTS AND DISCUSSION

Some of the results are shown in Figures 6 and 9 inclusive. Figures 6, 7 and 8 show the average mass depositions per tree in particular downstream rows from the spraying nozzle. The average mass is expressed as percentage of the total mass deposited on all instrumented trees. Results are given for both low and high values of the inductive voltage [3 and 10 kV].

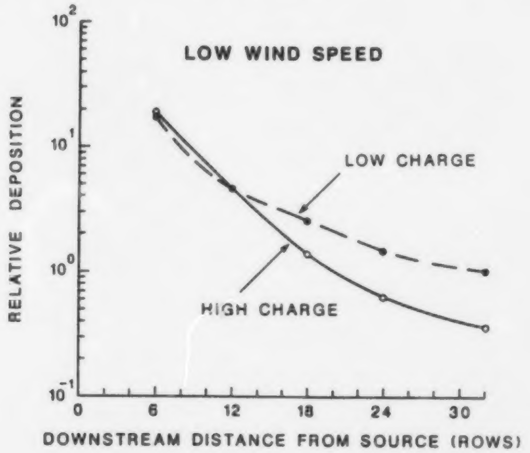

FIGURE 6: SUMMARY OF RELATIVE DEPOSITION AT 1 ft/sec. (0.3 m/s)

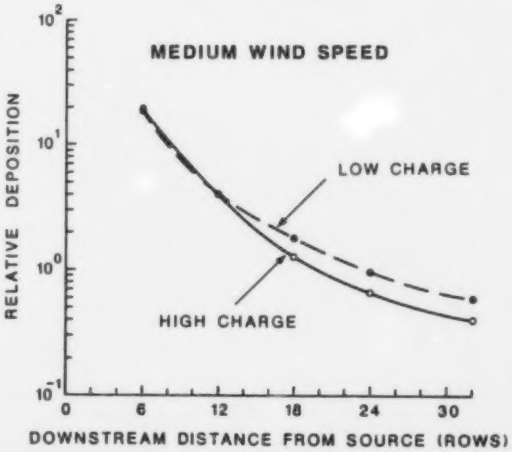

FIGURE 7: SUMMARY OF RELATIVE DEPOSITION AT 2 ft/sec. (0.6 m/s)

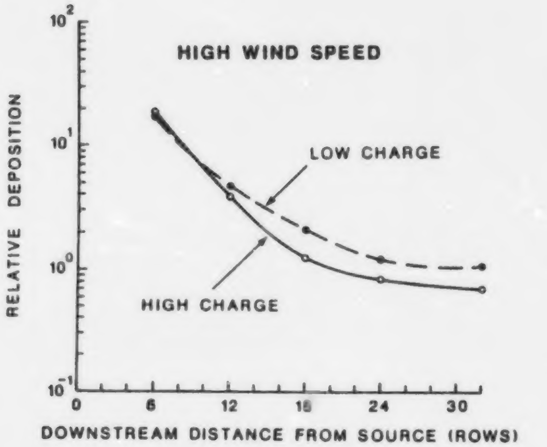

FIGURE 8: SUMMARY OF RELATIVE DEPOSITION AT 5 ft/sec (1.5 m/s)

One observes that at distances close to the spray nozzle the deposited mass is substantially larger at the high induction charging thus depleting the cloud more rapidly. This more rapid depletion of the cloud, results in lower relative deposition at greater distances from the nozzle. Hence, there is less drift and less contamination of adjacent areas. These findings are consistent with theoretical expectations. Close to the spraying nozzle, under the influence of the larger space charge represented by the cloud of droplets, the electrical forces of attraction to the ground, deposit a considerably larger quantity of mass.

Further downwind, where the droplet concentration and hence the electric-space charge density are considerably smaller, the electrical forces become negligible. The gravitational and turbulence mixing forces dominate and the depleted cloud will deposit less mass.

Figure 9 shows the % mass (deposition contours) in terms of the total mass deposited for 3 wind speeds. It is interesting to note the considerable air entrainment of the sprayed droplets. The mass contours change shape with increasing wind speed. At high wind speeds the nozzle exit velocity becomes less important and the spray is mainly carried in the direction of the wind.

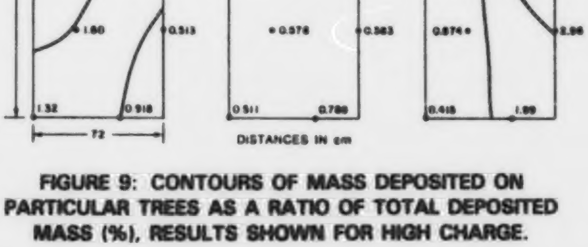

FIGURE 9: CONTOURS OF MASS DEPOSITED ON PARTICULAR TREES AS A RATIO OF TOTAL DEPOSITED MASS (%), RESULTS SHOWN FOR HIGH CHARGE.

CONCLUSIONS

The described experimental method using boundary layer wind tunnel facilities and electric charge collectors present substantial advantages to complement and/or replace existing methods in special cases.

A. It allows an immediate quantitative measurement of the surface deposition patterns eliminating lengthy and time consuming counting and/or chemical methods.

B. With adequate modelling of the forest or orchard, it allows researchers to study the drift of the insecticide clouds under all wind conditions in the respective boundary layer. Current methods in actual field tests are highly complicated by the unpredictable and fast-changing wind conditions at the time of the test.

C. Using differently designed model trees, the same method may be used to measure the penetration of mass inside the tree canopies.

D. The experiments clearly demonstrate the effectiveness of charging the droplets. At locations near the nozzle, charging the droplets results in a somewhat increased deposition and hence greater spraying efficiency, see Figures 6 to 8. At further distances, the deposition is significantly reduced and charging the droplets results in less drift.

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